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FLIGHT TEST OF AN 8000 PSI LIGHTWEIGHT HYDRAULIC SYSTEM (LHS).(U)
APR 77 J N DEMARCHI, R K HANING N62269-76-C-0254
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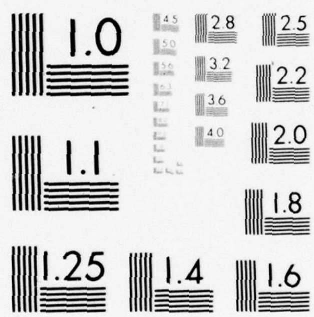

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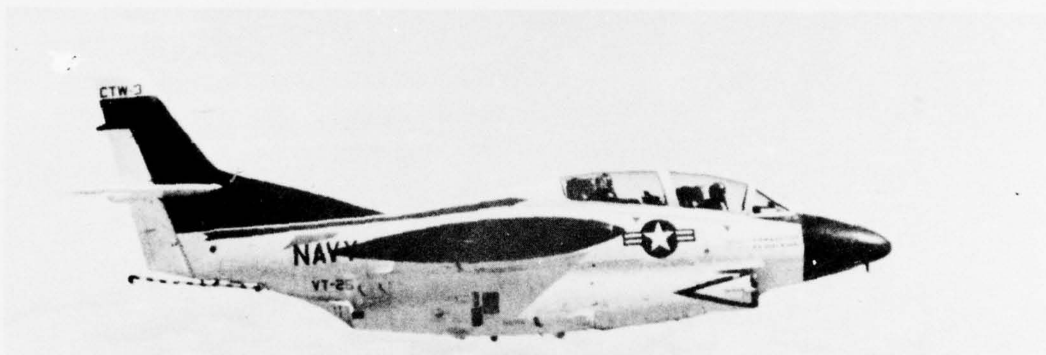
FLIGHT TEST of an 8000 psi LIGHTWEIGHT HYDRAULIC SYSTEM



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APRIL 1977

Rockwell International

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Prepared For:

NAVAL AIR SYSTEMS COMMAND (AIR 340C)
Department of the Navy
Washington, D.C. 20361

AIR VEHICLE TECHNOLOGY DEPARTMENT (30211)
Naval Air Development Center
Warminster, PA 18974

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

An 8000 psi hydraulic lateral control system was installed in a T-2C airplane. Four pilots evaluated the test installation, accumulating 11.5 flight hours. Operational characteristics were very similar to the original 3000 psi system. The 8000 psi installation functioned exceptionally well. Successful completion of this project confirmed that 8000 psi lightweight hydraulic systems can be designed, fabricated, and maintained without special techniques or state-of-the-art advances.

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SUMMARY

The U.S. Navy is funding a program to develop lightweight hydraulic systems (LHS) for aircraft; this report documents Phase IX. Prior phases have shown that use of an 8000 psi operating pressure instead of the conventional 3000 psi level would significantly reduce weight and space requirements of hydraulic system components. The primary objective of Phase IX was to provide further evidence of the feasibility of the LHS concept by flight testing an 8000 psi hydraulic control system.

An 8000 psi lateral control system was installed in a T-2C airplane using components developed in prior phases of the program. Major components were an 8000 psi variable displacement pump and an 8000 psi aileron power actuator. Four different pilots evaluated the test installation, accumulating a total of 11.5 flight hours. No malfunctions occurred in the 8000 psi system; pilot comments were favorable. Operational characteristics of the 8000 psi system were very similar to the T-2C 3000 psi lateral control system. The test installation performed exceptionally well; fluid temperatures were nominal, pressure fluctuations were small, fluid particulate generation was low, and component endurance was projected to be satisfactory.

Successful completion of Phase IX corroborated the results of prior analyses and laboratory investigations. The relative ease with which flight testing was accomplished confirmed that 8000 psi lightweight hydraulic systems can be designed, fabricated, and maintained without special techniques or state-of-the-art advances.

PREFACE

This report documents research conducted by the Columbus Aircraft Division of Rockwell International Corporation, Columbus, Ohio under Contract N62269-76-C-0254 with the Naval Air Development Center, Warminster, Pennsylvania. Technical direction was administered by Mr. J. Ohlson, Head, Fluid Systems Section, Air Vehicle Technology Department, Naval Air Development Center (30211), and Mr. N. Webb, Head, Fluid Systems Section, Mechanical Equipment Branch, Naval Air Systems Command (AIR-53031).

This report discusses a flight program conducted on an 8000 psi hydraulic lateral control test installation in a T-2C airplane. This work was related to tasks performed under Contract NOw-65-0567-d, N00019-68-C-0352, N00156-70-C-1152, N62269-71-C-0147, N62269-72-C-0381, N62269-73-C-0700, N62269-74-C-0511, and N62269-75-C-0422.

Acknowledgement is given to the following for their participation on this project.

Mr. B. Holland	Systems Engineer
Mr. W. Kniepkamp	Flight Test Project Engineer
Mr. R. Cockburn	Test Pilot
Mr. E. Gillespie	Chief Test Pilot
Mr. A. Lane	Manager, Flight Operations (and Test Pilot)
Mr. R. Wenzell	Director, Flight Operations and Logistics (and Test Pilot)
LCdr. R. Carter	Government Flight Representative

Appreciation is extended to the many individuals who provided helpful support and constructive criticism of the program; in particular, Mr. J. Crowder and Mr. N. Webb of the Naval Air Systems Command, Mr. J. Ohlson and Mr. J. Dever of the Naval Air Development Center, and Dr. F. Bellar, Jr. of the Columbus Aircraft Division of Rockwell International.

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1.0 INTRODUCTION

1.1 BACKGROUND INFORMATION

The development of a lightweight hydraulic system (LHS) for military aircraft has been a joint undertaking by the Navy and Rockwell International since 1966. The LHS concept involves the use of an 8000 psi pressure level to minimize the weight and space requirements of hydraulic components and lessen the severity of the weight and space restrictions present in high density, supersonic aircraft.

Prior phases of the program have examined many aspects of very high pressure hydraulic systems as applied to aircraft. The first phase was a theoretical study of pressure levels up to 20,000 psi, and concluded that operating pressures up to 9000 psi are feasible, Reference 1. The second phase consisted of: (1) a math model computer simulation to establish the dynamic response of two schematically simple hydraulic systems operating with pressures up to 12,000 psi; and (2) laboratory tests to confirm trends noted at lower pressures and gain operating experience with pressure levels up to 9000 psi, Reference 2. Phase III verified the math model dynamic response at 6000 and 9000 psi by means of laboratory tests conducted on a mass-loaded servo actuator powered by a very high pressure aircraft-type pump, Reference 3. The pump was designed and built by Abex Corporation in Oxnard, California, under the technical guidance of the Columbus Aircraft Division (CAD). The 9000 psi servo actuator was designed and fabricated by CAD and sized to simulate the RA-5C horizontal stabilizer flight control "muscle" actuator.

Phase IV involved hardware performance tests, selection of 8000 psi as the LHS operating pressure level, development of LHS design criteria, and use of these criteria in a study made to determine space and weight savings achieved if an 8000 psi hydraulic system were applied to the F-14 airplane, Reference 4. Phase V was an investigation of the detail performance characteristics of 8000 psi hardware including a variable delivery pump, three port solenoid valve, power servo actuator, and notched spool/sleeve type flow control valve -- all operating with MIL-H-83282 fluid, Reference 5. In addition, the computer simulation of Reference 3 was updated and compared to hardware performance, and an industry-wide survey was made to locate 8000 psi static and dynamic seals. Phase VI consisted of preparations for conducting an endurance test on aircraft-type hardware designed for use in an 8000 psi hydraulic system, Reference 6.

Phase VII was a 100 hour endurance test conducted at 8000 psi and +200°F on lightweight hardware in a laboratory hydraulic system designed to be representative of aircraft-type circuitry. The hardware cycled were: pump, relief valve, restrictors, solenoid valves, flow control valve, seals (22), hydraulic fluid (MIL-H-83282), tubing, fittings, and hoses. The test was completed with no major problems. This phase also included the design and fabrication of an 8000 psi aileron actuator for the T-2C airplane, Reference 7.

Phase VIII involved preparations for flight testing an 8000 psi lateral control system test installation on a T-2C. The major tasks were test installation design, heat rejection analysis, and laboratory compatibility tests of system components, Reference 8.

The lightweight hydraulic system development program has shown that significant advantages can be gained, in terms of weight savings, reduced volume requirements, and lower overall costs, by operating at 8000 psi instead of the conventional 3000 psi level.

1.2 OBJECTIVES

Objectives of Phase IX of the LHS development program were:

(1) Replace the 3000 psi lateral control system on a T-2C airplane with the 8000 psi system designed in Phase VIII.

(2) Conduct preflight checks on the test installation.

(3) Conduct flight tests and endurance evaluation on the 8000 psi system.

(4) Confirm the feasibility of the LHS concept by:

- Demonstrating that prior analyses are valid
- Proving that 8000 psi hydraulic systems for aircraft can be designed, fabricated, and maintained without special procedures.

1.3 TECHNICAL APPROACH

The test system and hardware developed in prior phases of the LHS program were installed in a bailed T-2C airplane. (The T-2C is a two-place, twin engine turbojet used for pilot basic training.) The existing hydraulic system was altered so that the 3000 psi pump on the right hand engine powered only the elevator system, landing gear, arresting hook, and speed brakes. The 3000 psi pump on the left hand engine was replaced with an 8000 psi pump and the 3000 psi aileron actuator was replaced with an 8000 psi unit. The existing reservoir and return lines were common to both the 3000 psi and 8000 psi systems.

Performance of the test installation was monitored by measuring pertinent pressures, temperatures, and flows. Standard parameters, such as airspeed, altitude, engine RPM, etc., were measured with existing instrumentation. Flight data were recorded on an oscillograph or a photo recorder depending on the parameter.

Preflight tests were conducted to checkout system operation and instrumentation, and determine if any destructive vibration, hydraulic resonance, or heat buildup occur under normal operating conditions. A flight plan was established to evaluate the 8000 psi system.

Eleven hours of flight time were logged on the test installation at various altitudes and airspeeds. Pilot observations and instrumentation data were used as a basis for evaluating the system.

2.0 T-2C AIRPLANE

2.1 GENERAL DESCRIPTION

The T-2C "Buckeye" is currently in production at the Columbus Aircraft Division (CAD) of Rockwell International. The Buckeye is a two-place, subsonic trainer powered by twin turbojet engines. The aircraft is designed for both land and carrier based operations. Distinguishing features include wide-track tricycle landing gear, straight tapered wings, and low slung intake ducts, Figure 1.

The T-2C is used as a basic trainer for military pilots, and is equipped for cross-country flight, night flying, and low altitude, high speed navigation exercises. Maximum level flight speed of the Buckeye is 465 knots at 15,000 ft.; the service ceiling is 45,000 ft. Takeoff and landing speeds are in the range of 95 to 110 knots. A typical takeoff gross weight is 13,000 lb.

Dual power sources are provided for the electrical, hydraulic, and air conditioning systems. The flight control system includes hydraulic full-powered ailerons, a boosted elevator, and an electric trim system; rudder operation is manual. The aileron and elevator actuators are part of mechanical linkage connecting the pilot's stick to the control surfaces. Thus, in the event of a hydraulic system malfunction, control of the aircraft can be accomplished manually.

2.2 HYDRAULIC SYSTEM

The T-2C has a 3000 psi, Type II (-65 to +275°F), single hydraulic system. Two pumps, one on each engine, provide power to operate the landing gear, speed brakes, arresting hook, aileron actuator, and elevator boost package. The pumps are constant pressure, variable delivery, axial piston units. Each pump is capable of delivering 4.9 gpm at 7800 rpm (8.1 hp). Hydraulic fluid is supplied to the pumps by an air/oil type reservoir pressurized by engine bleed air. Fluid cleanliness is maintained by 5 micron absolute filters. The system is illustrated schematically on Figure 2.

One pump can adequately handle all flow demands. However, if supply pressure should drop below 1800 psi, a priority valve is used to insure operation of the aileron and elevator actuators. A cockpit controlled shutoff valve is installed in the aileron/elevator sub-system to permit simulating loss of power for training purposes. The landing gear and arresting hook can be lowered and locked by gravity, if desired. The wheel brakes have an independent hydraulic system.

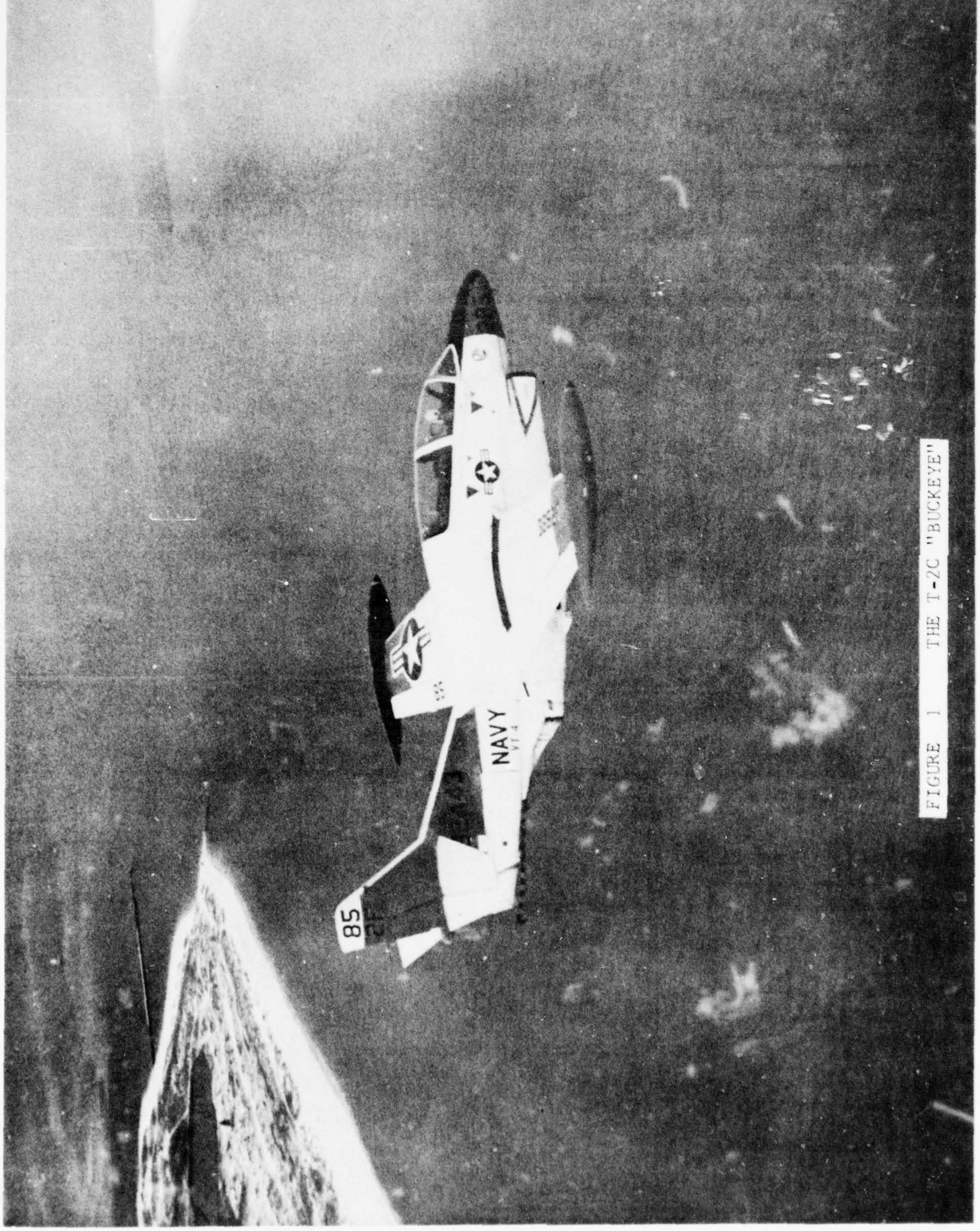


FIGURE 1 THE T-2C "BUCKEYE"

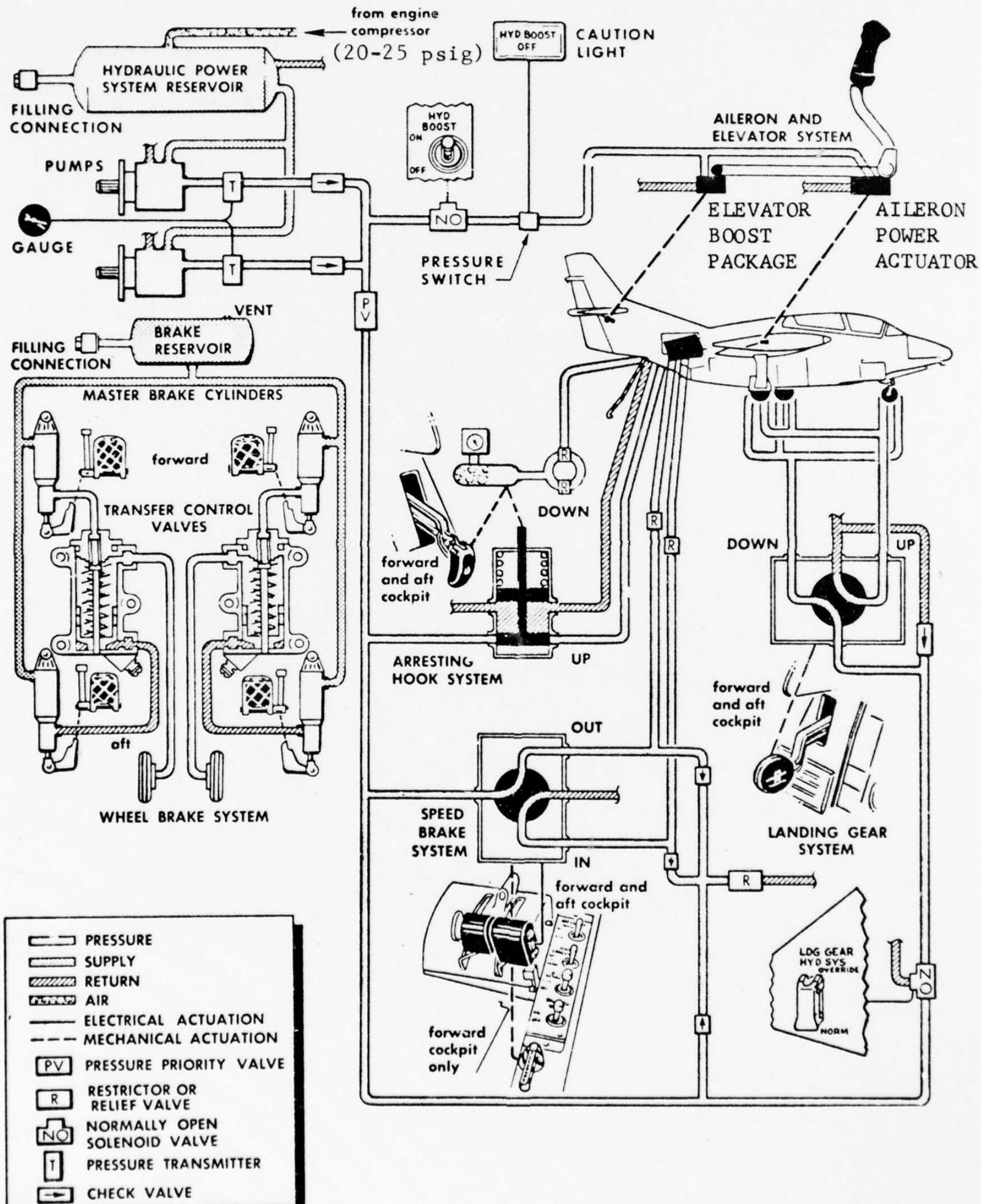


FIGURE 2 SCHEMATIC ILLUSTRATION OF T-2C HYDRAULIC SYSTEM

3.0 8000 PSI TEST INSTALLATION

3.1 HYDRAULIC SYSTEM

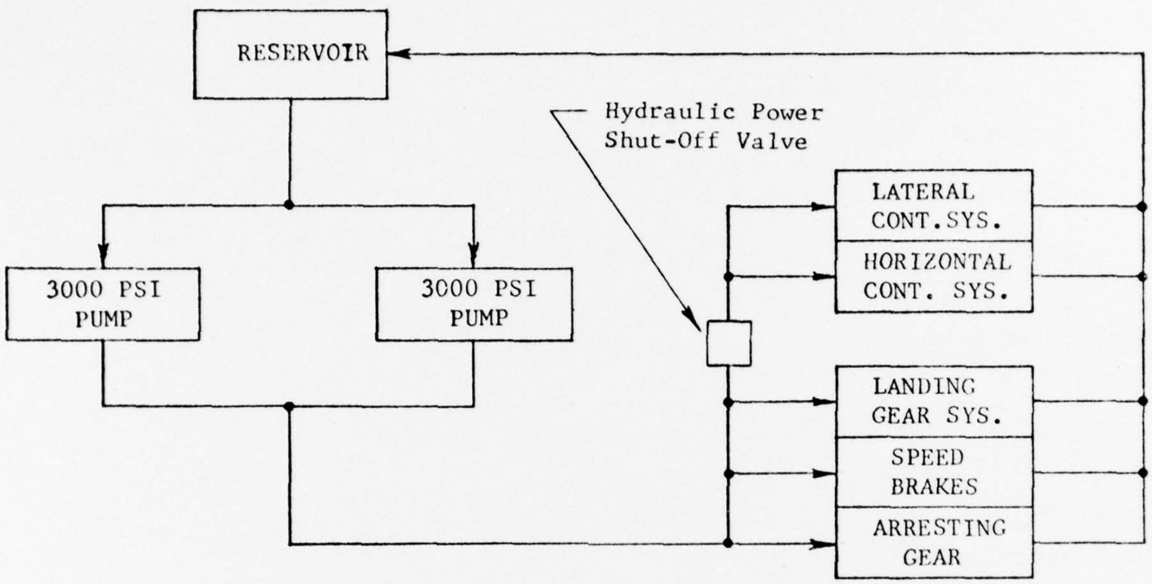
The lateral control system in the bailed T-2C (BuNo. 152382) was modified to operate at 8000 psi. A 3.4 gpm, 8000 psi pump on the No. 1 engine powered an 8000 psi aileron actuator; a 4.9 gpm, 3000 psi pump on the No. 2 engine powered all remaining T-2C hydraulic sub-systems. The 3000 and 8000 psi systems utilized a common reservoir and common return lines. The existing and modified hydraulic systems are compared schematically on Figure 3. Major changes required in the T-2C hydraulic system to accommodate the test installation are listed below:

- The 3000 psi hydraulic pump on the No. 1 (LH) engine was replaced with a GFE 8000 psi pump.
- The T-2C 3000 psi aileron power actuator was replaced with the LHS 8000 psi actuator built in Phase VII, Reference 7.
- 3000 psi lines from the pump to the aileron actuator were replaced with 8000 psi tubing, fittings, and hoses.
- A relief valve and solenoid valve were installed in the 8000 psi system.
- A heat exchanger was installed in the common case drain line of the two pumps.
- MIL-H-5606 fluid in the T-2C was replaced with MIL-H-83282 fluid.

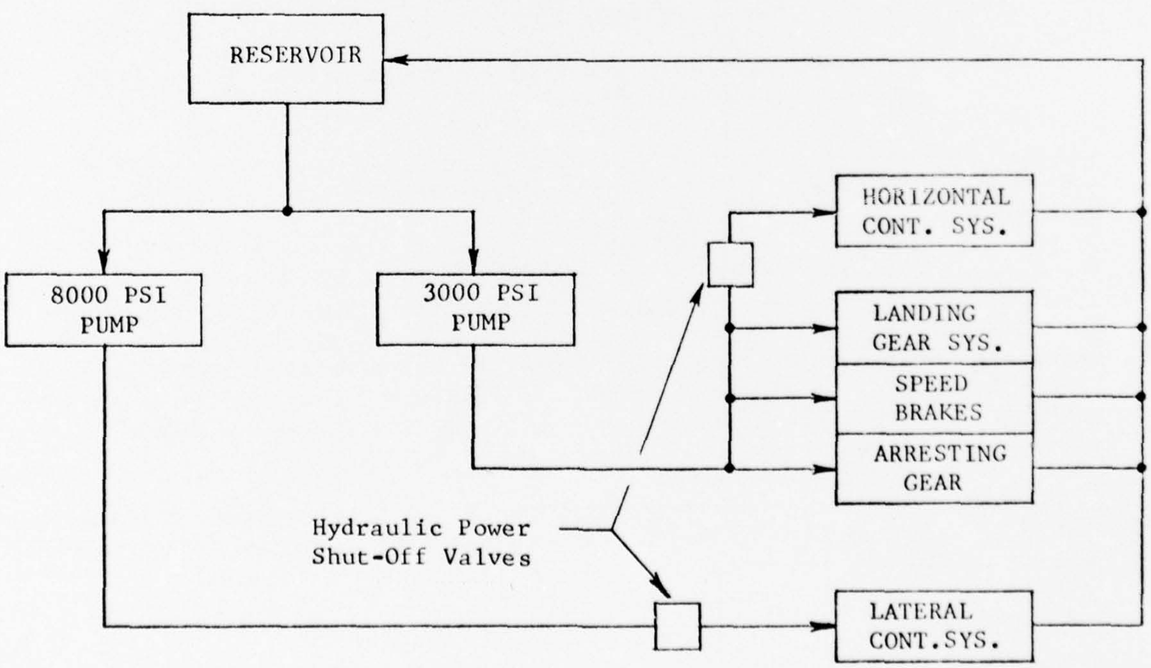
The modified system is shown schematically on Figure 4. Major 8000 psi components are listed in Table I. Component details are described in Reference 8.

The general location of the test installation is shown on Figure 5. The 8000 psi lines followed identical routing of the original 3000 psi lines to a compartment aft of a fuel cell and above the engines where all LHS components were located except the pump. Plumbing details are given in Figure 6. A view of plumbing in the aft fuselage compartment is shown on Figure 7. Photographs of the 8000 psi pump and aileron actuator installations are presented as Figures 8 and 9.

A thermal analysis performed in Reference 8 indicated a heat exchanger would be required for hot weather ground operations. This was primarily the result of (1) the small surface area and volume of the 8000 psi system, and (2) the oversize 8000 psi pump. The 8000 psi pump can deliver 15.5 hp, whereas one T-2C pump delivers 8.1 hp maximum.



EXISTING 3000 PSI SYSTEM



MODIFIED HYDRAULIC SYSTEM

FIGURE 3 EXISTING AND MODIFIED HYDRAULIC SYSTEMS

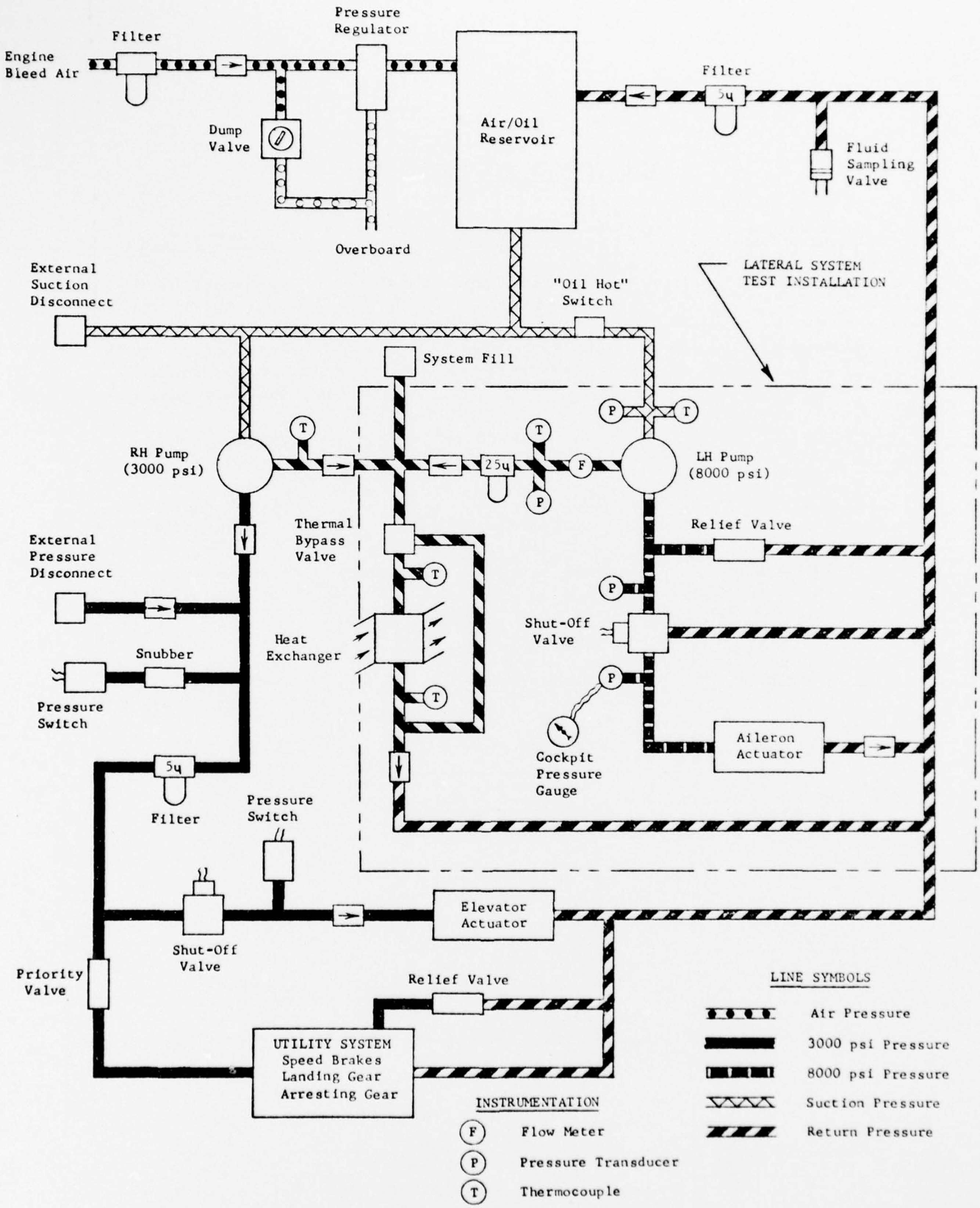


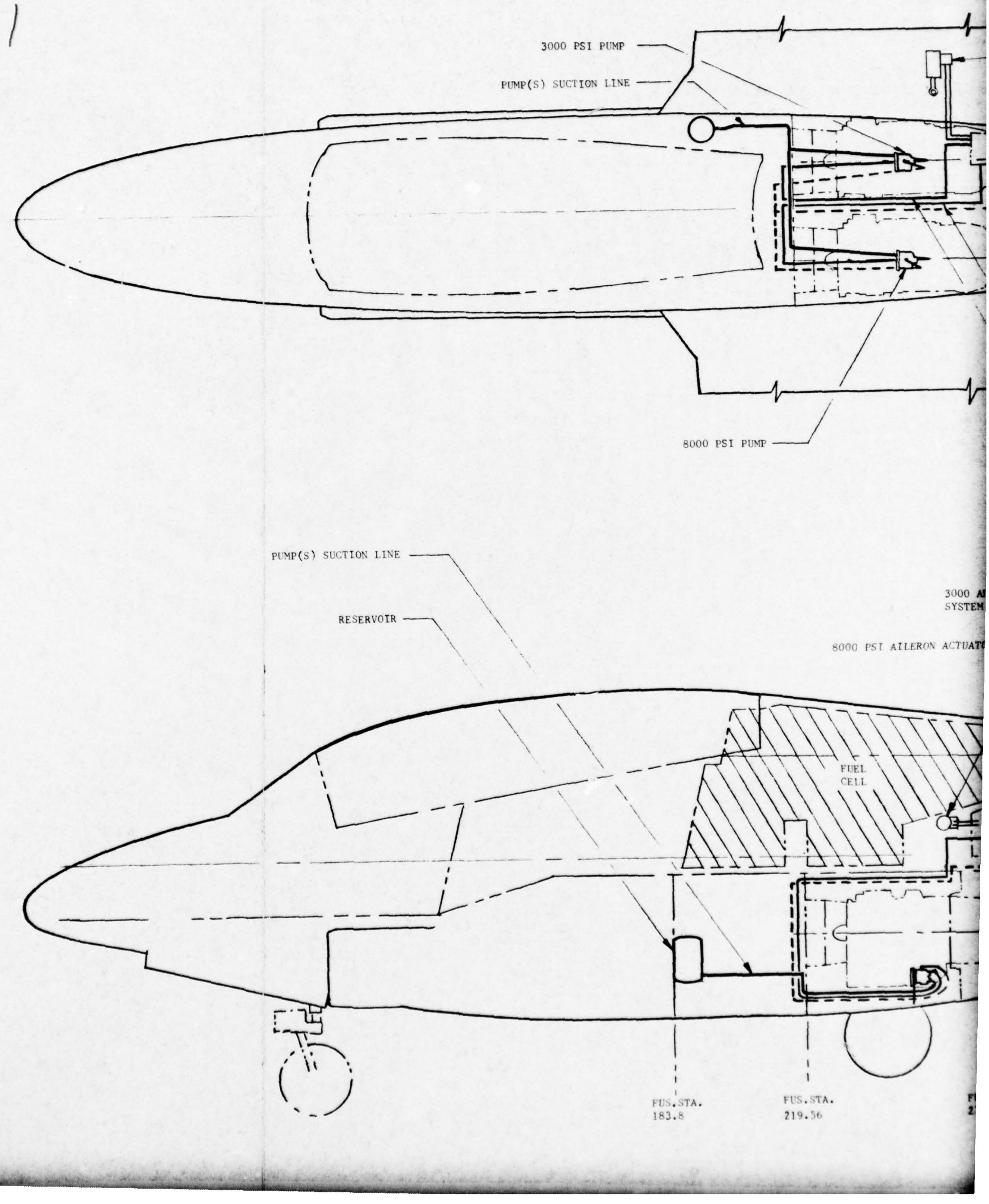
FIGURE 4 SCHEMATIC DIAGRAM OF MODIFIED HYDRAULIC SYSTEM

TABLE I

LIST OF 8000 PSI COMPONENTS

PART NUMBER	DESCRIPTION	MANUFACTURER
AP1V-106	Variable displacement pump	Aerospace Division of Abex Corporation
4257-01	Aileron power actuator	Columbus Aircraft Division of Rockwell International
1180A	Hydraulic relief valve	PneuDraulics, Inc.
15390-1	Shut-Off valve	Sterer Engineering & Manufacturing Co.
37404004-0264C	Hose	Titeflex Division of Atlas Corporation
R44598-0310	Hose	Resistoflex Corporation
21-6-9 CRES	Tubing	Trent Tube Division of Colt Industries
Dynatube Series	Fittings	Resistoflex Corporation
MIL-H-83282	Hydraulic Fluid	Royal Lubricants Co.

NOTE: 8000 psi instrumentation is not included in this listing, reference Section 3.2.



3000 PSI PUMP
PUMP(S) SUCTION LINE
8000 PSI PUMP
PUMP(S) SUCTION LINE
RESERVOIR
3000 A
SYSTEM
8000 PSI AILERON ACTUATO
FUEL
CELL
FUS.STA.
183.8
FUS.STA.
219.56

2

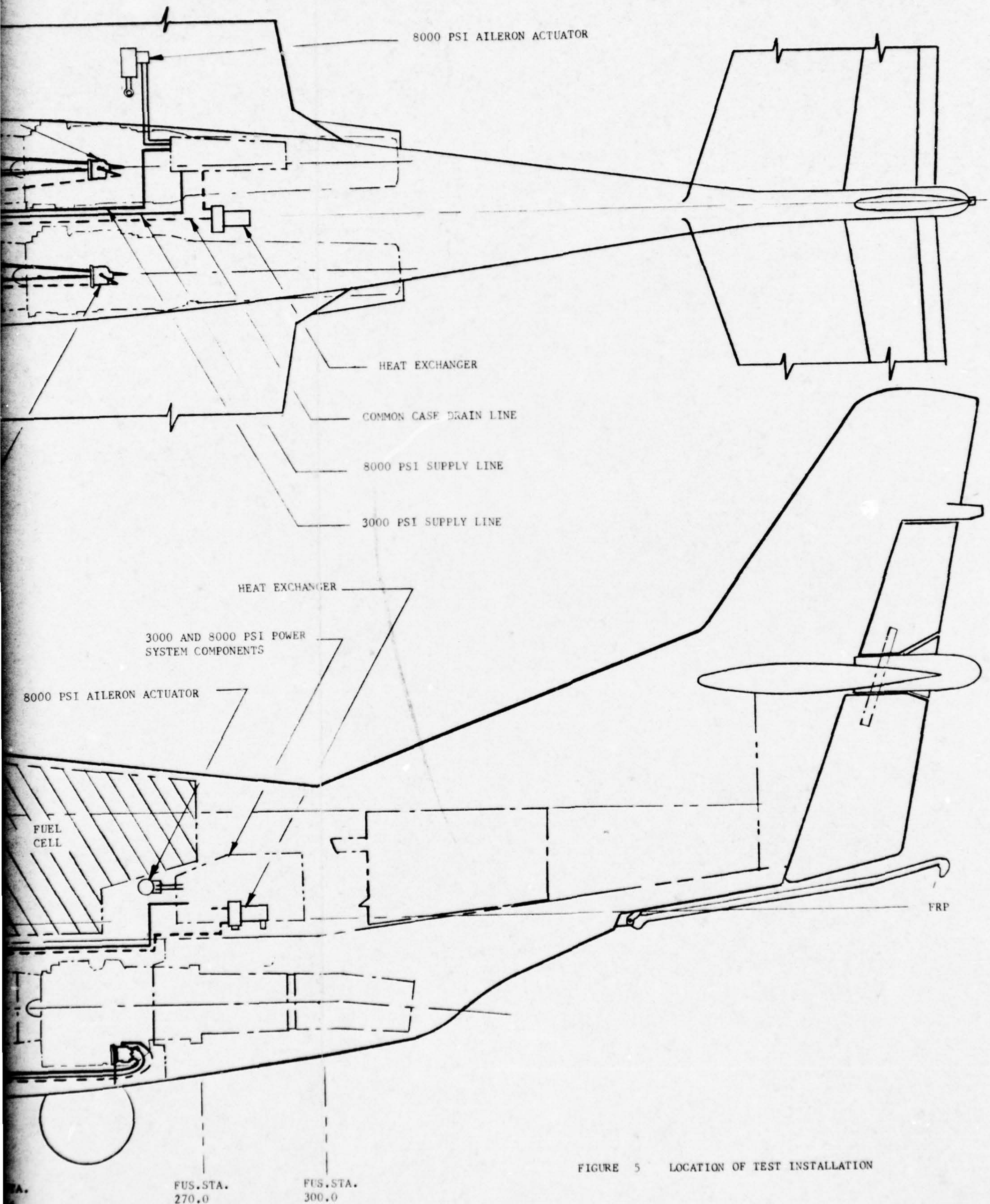


FIGURE 5 LOCATION OF TEST INSTALLATION

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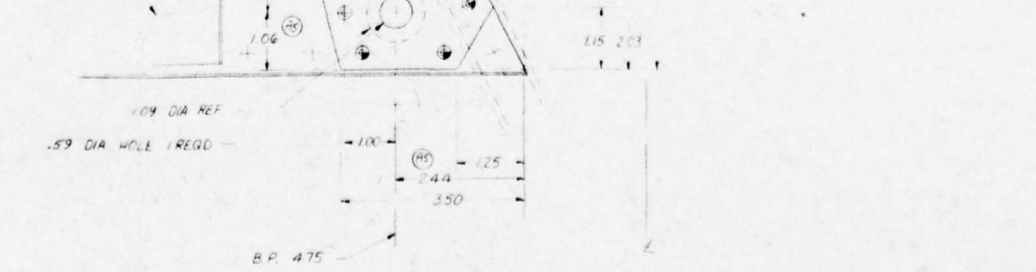
R44118T-06
LD153-0011-0024

SD 4266-02-01



VIEW A - A

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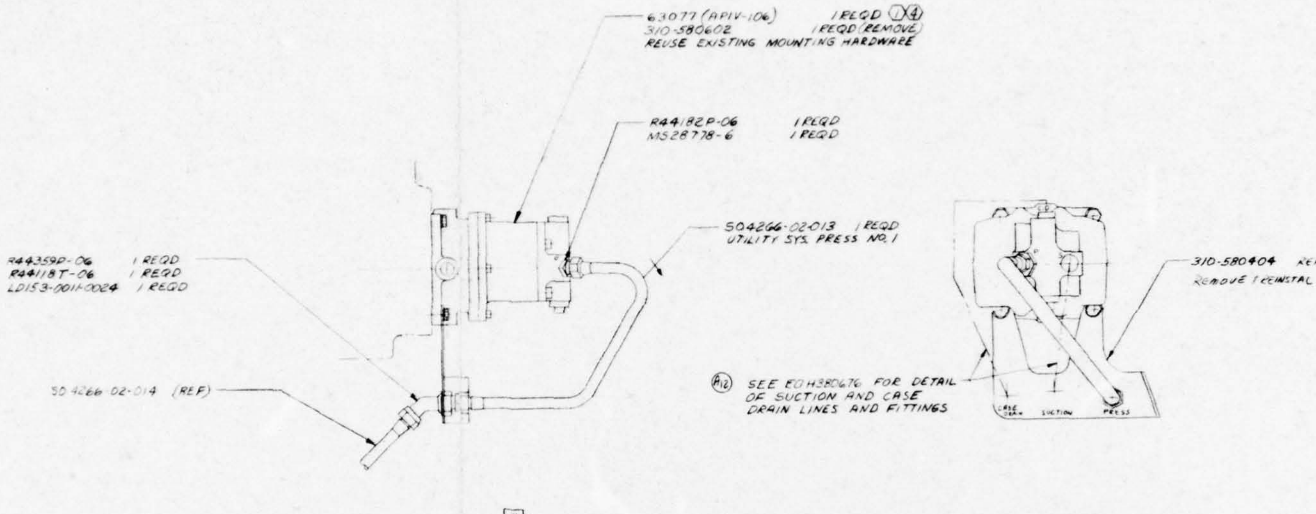
(FULL SIZE)



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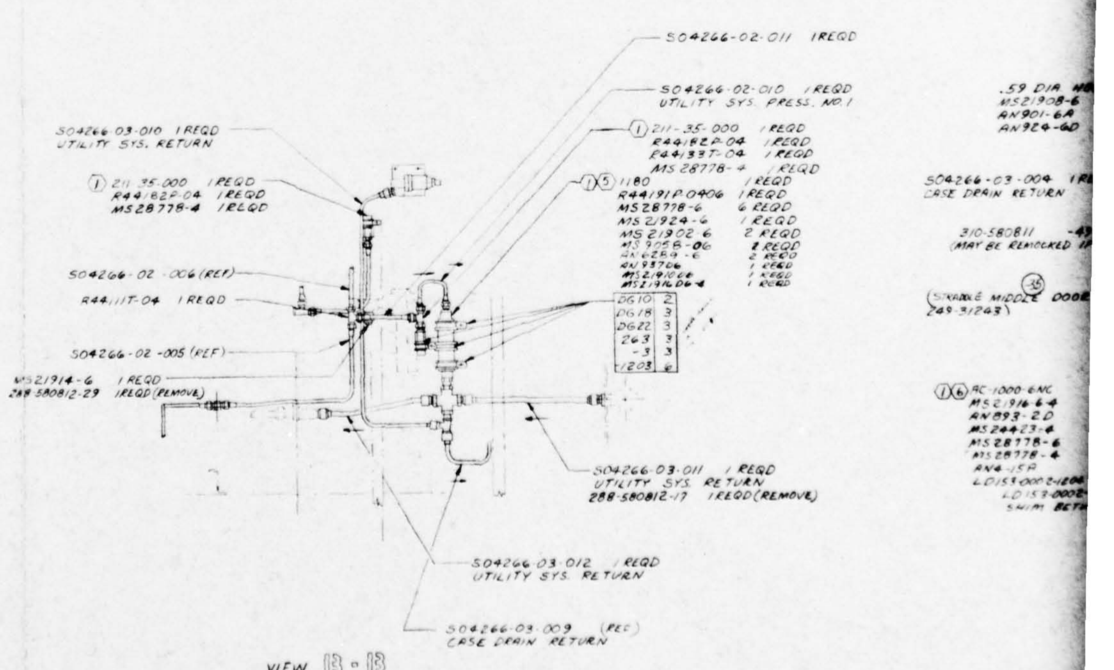

VIEW B-B

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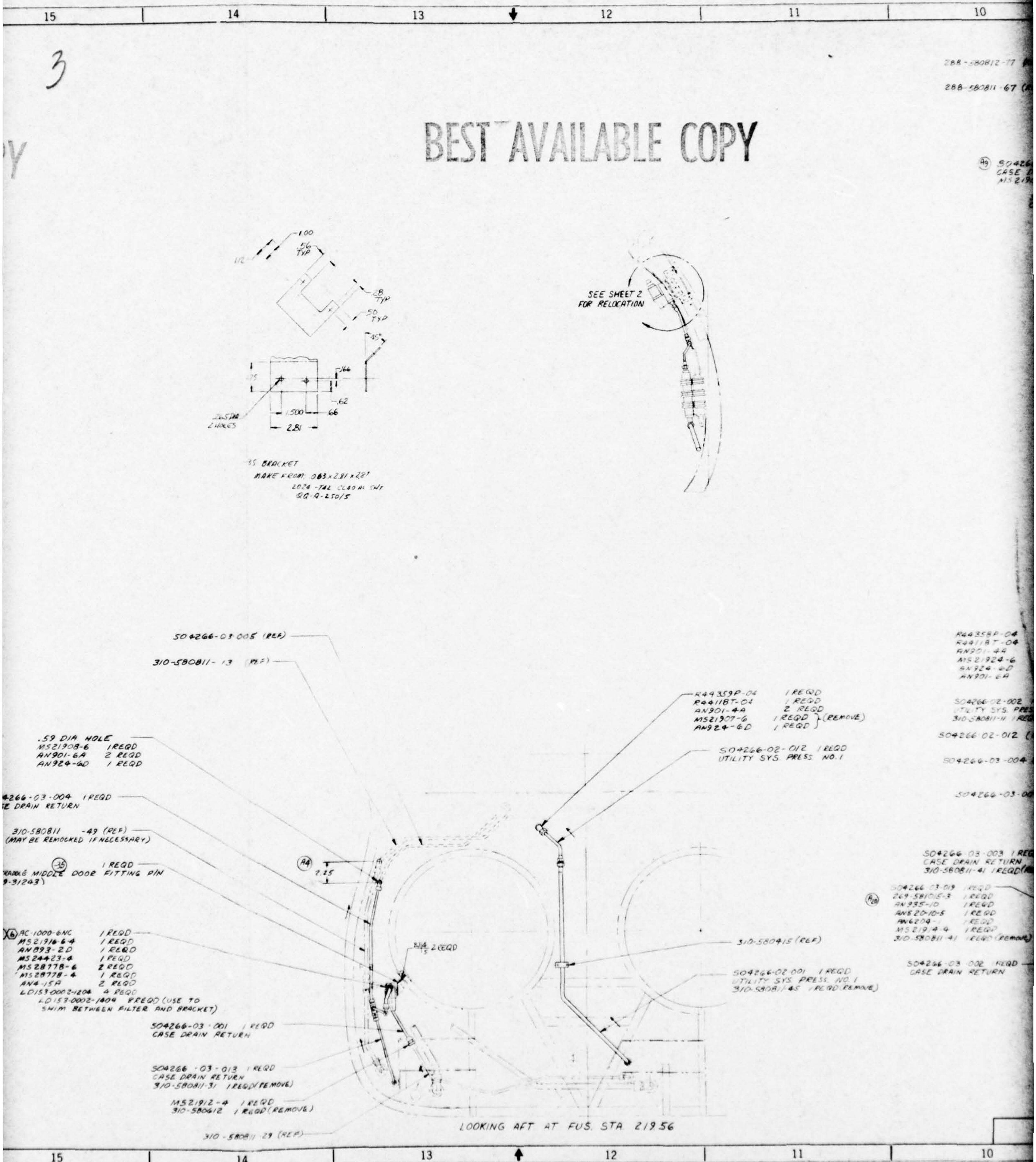
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SEE SHEET 2
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.56 TYP
.28 TYP
.50 TYP
45°
.166
.62
1.500
.66
2.81
35 BRACKET
MAKE FROM .063 x 2.81 x 2.87
2024-T42 CLAD AL SHT
QQ-A-250/5
504266-03-005 (REF)
310-580811-13 (REF)
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R44118T-04 1 REQD
AN901-4A 2 REQD
MS21907-6 1 REQD
AN924-6D 1 REQD
(REMOVE)
504266-02-012 1 REQD
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AN901-6A 2 REQD
AN924-6D 1 REQD
4266-03-004 1 REQD
E DRAIN RETURN
310-580811 -49 (REF)
(MAY BE RELOCATED IF NECESSARY)
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9-31243)
A4
2.25
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MS28778-6 2 REQD
MS28778-4 1 REQD
AN4-15A 2 REQD
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310-580612 1 REQD (REMOVE)
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LOOKING AFT AT FUS. STA. 219.56
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AN924-6D
AN901-6A
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504266-03-00
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AN6204-1 1 REQD
MS21914-4 1 REQD
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CASE DRAIN RETURN
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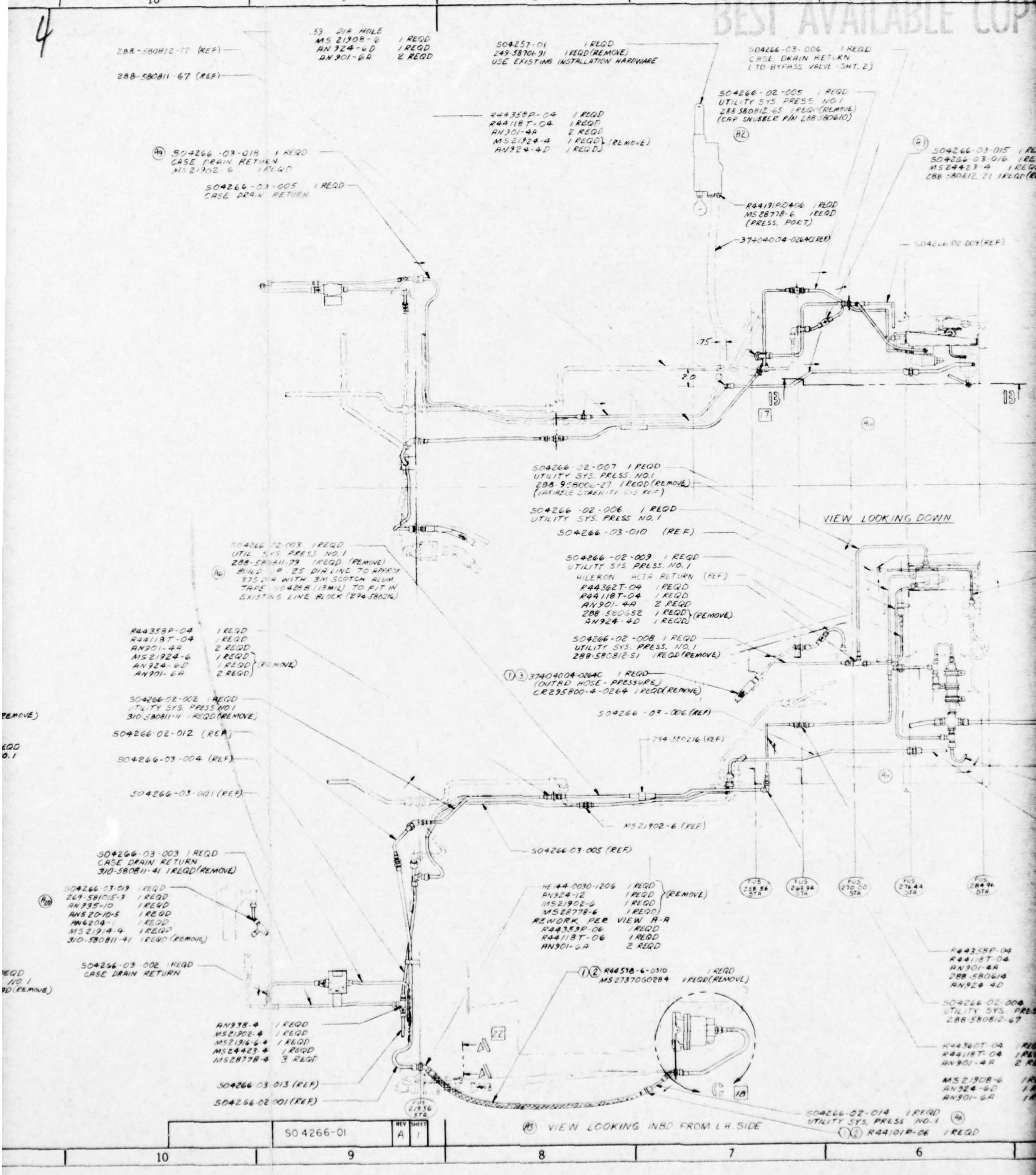
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10
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6
.53 DIA HOLE
MS 21908-6 1 REQD
AN 924-6D 1 REQD
AN 901-6A 2 REQD
288-580812-77 (REF)
288-580811-67 (REF)
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(TO BYPASS VALVE SHT. 2)
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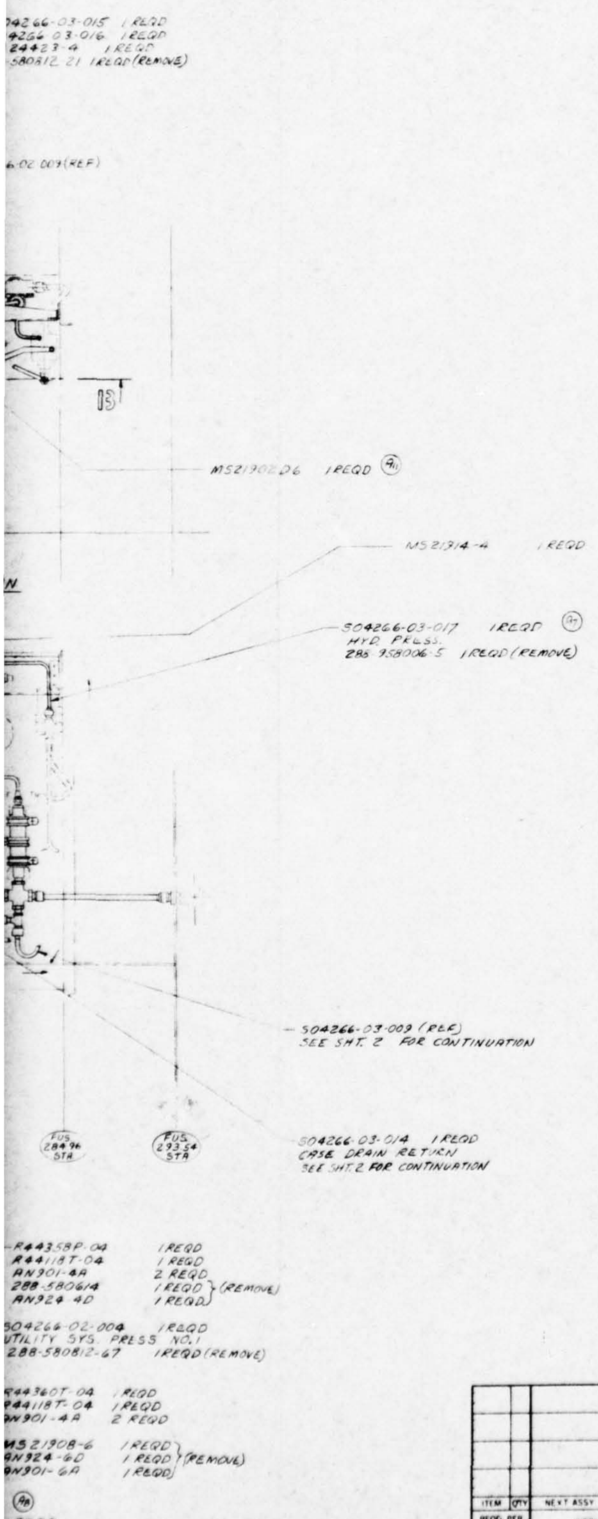
FUS 284.96 STA
HE144-0030-1206 1 REQD
AN924-12 1 REQD
MS21902-6 1 REQD
MS28778-6 1 REQD
(REMOVE)
REWORK PER VIEW A-A
R44358P-06 1 REQD
R44118T-06 1 REQD
AN901-6A 2 REQD
S04266-03-002 1 REQD
CASE DRAIN RETURN
1 2 R44518-6-0310 1 REQD
MS27370G0284 1 REQD (REMOVE)
R44358P-04
R44118T-04
AN901-4A
288-580614
AN924-4D
S04266-02-004
UTILITY SYS. PRESS
288-580812-67
AN938-4 1 REQD
MS21902-4 1 REQD
MS21916-6-4 1 REQD
MS24423-4 1 REQD
MS28778-4 3 REQD
22
R44360T-04
R44118T-04
AN901-4A
MS21908-6
AN924-6D
AN901-6A
S04266-03-013 (REF)
S04266-02-001 (REF)
18
FUS 219.56 STA
S04266-02-014 1 REQD
UTILITY SYS. PRESS NO.1
1 2 R44101P-06 1 REQD
A8 VIEW LOOKING INBD FROM L.H. SIDE
S0 4266-01
REV A
SHEET 1

E COPY 5



REVISIONS

ZONE	LTR	DESCRIPTION	DISPN	DATE	APPROVED
		1 MAY BE REWORKED 2 CANNOT BE REWORKED 3 RECORD CHANGE 4 NOW SHOP PRACTICE 5 PARTS MADE OK			
	A				
6	1	ADDED CALLOUT: 504266-03-015 1 REQD, 504266-03-016 1 REQD, MS24423-4 1 REQD, 288-580812-25 1 REQD (REMOVE)	3		
7	2	ADDED CALLOUT 288-580812-65 1 REQD (REMOVE) CAP SNUBBER P/N 288-580610.	3		
7/8	3	"VIEW LOOKING INBD FROM LH SIDE" (WAS) "VIEW LOOKING OUTBD RH SIDE"	3		
14	4	ADDED 2.25 DIM	3		
22	5	ADDED 1.06 AND 2.44 DIMS	3		
9	6	ADDED NOTE TO 504266-02-003 LINE CALLOUT.	3		
4	7	ADDED 504266-03-017 1 REQD. 288-958006-5 1 REQD (REMOVE)	3		
6	8	ADDED 504266-02-014 1 REQD, R44101F-06 1 REQD CODE 1 & 2	3		
10	9	ADDED 504266-03-018 1 REQD, MS21902-6 1 REQD	3		
6	10	REMOVED PICTURE AND CALLOUTS FOR INITIAL LOCATION OF HEAT EXCH.	3		
5	11	ADDED MS21902D6 1 REQD	3		
17	12	"EOH 380676 (WAS)" INSTRUMENTATION	3		
35	13	.1935 (WAS) .0935	3		
37	14	EOH 380677-011 (REF) (WAS) 504266-03-009 1 REQD	3		
39	15	EOH 380677-021 (REF) (WAS) 504266-03-007 1 REQD	3		
40	16	504266-03-014 (WAS) 504266-03-006	3		
39	17	AN814-2 (WAS) MS21913-2	3		
44	18	2.12 (WAS) 1.06	3		
41	19	ADDED 7-10° SCARF NOTE & .12 DIM	3		
10	20	ADDED 504266-019 1 REQD, 269-581015-3 1 REQD, AN935-10 1 REQD, AN520-10-5 1 REQD, AN6204-1 1 REQD	3		
P/L	21	REVISED P/L TO REFLECT ABOVE CHANGES		12-7-76	B. HOLLAND

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FIGURE 6

6. AIRCRAFT POROUS MEDIA INC., GLEN COVE N.Y.
5. PNEUDRAULICS, INC. 8961 CENTRAL AVE, MONTCLAIR, CALIF. 91763.
4. ABEX CORP, AEROSPACE DIV, 3151 W 5th ST. OXNARD CALIF. 93030.
3. TITEFLEX DIV OF ATLAS CORP., 306 HENDEE ST. SPRINGFIELD, MASS. 01104.
2. RESISTOFLEX CORP, ROSELAND N.J., 07068.
1. TO BE FURNISHED BY ENGINEERING.

NOTES UNLESS OTHERWISE NOTED

ITEM	QTY	NEXT ASSY	USED ON	END ITEM NO.	THRU
REQD PER END ITEM		APPLICATION		EFFECTIVITY	

HEAT TREAT

FINISH

FOR PARTS LIST SEE PL

UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES
MFG TOLERANCES ON
UNDIMENSIONED ± .03
XX (DECIMALS) ± .03
XXX (DECIMALS) ± .010
ANGLES ± 30'

HOLES NOTED			DRILL	
.013	THRU	.040	+ .001	- .001
.041	THRU	.130	+ .002	- .001
.131	THRU	.229	+ .003	- .001
.230	THRU	.500	+ .004	- .001
.501	THRU	.750	+ .005	- .001
.751	THRU	1.000	+ .007	- .001
1.001	THRU	2.000	+ .010	- .001

DO NOT SCALE PRINT

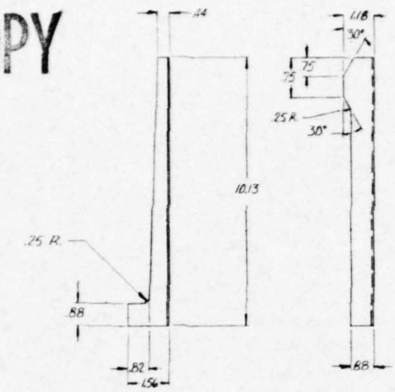
CONTR NO.
DWN BY B. C. HOLLAND
CHK BY
APVD

Rockwell International Corporation
Columbus Aircraft Division
Columbus, Ohio 43216

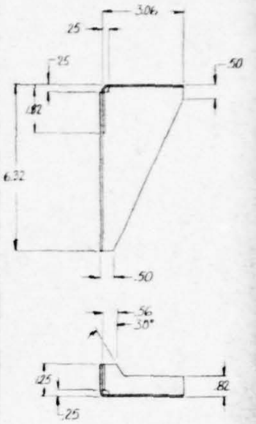
HYDRAULIC EQUIP INSTALLATION 8000PSI SYSTEM FOR T-2C AIRCRAFT

SIZE J | CODE IDENT NO. 89372 | 504266-01

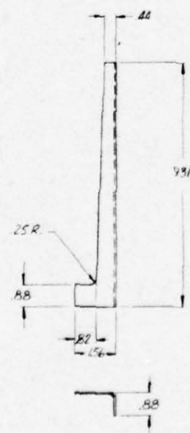
SCALE | SHEET 1 OF 2



-5 ANGLE
MAKE FROM: 2024-T42 CLAD AL SHT
QQ-A-250/5
.063 x 2.44 x 10.13

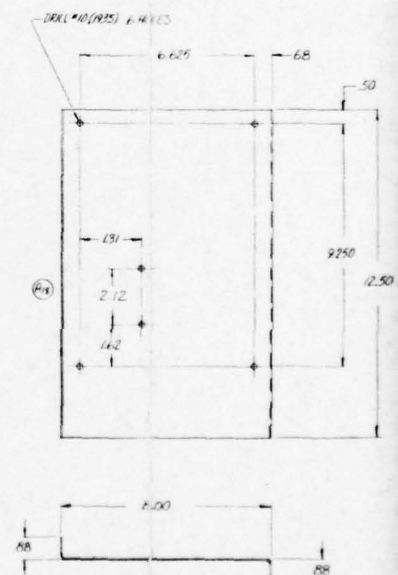


-9 BRACKET
MAKE FROM: 2024-T42 CLAD AL SHT
QQ-A-250/5
.063 x 4.88 x 7.57



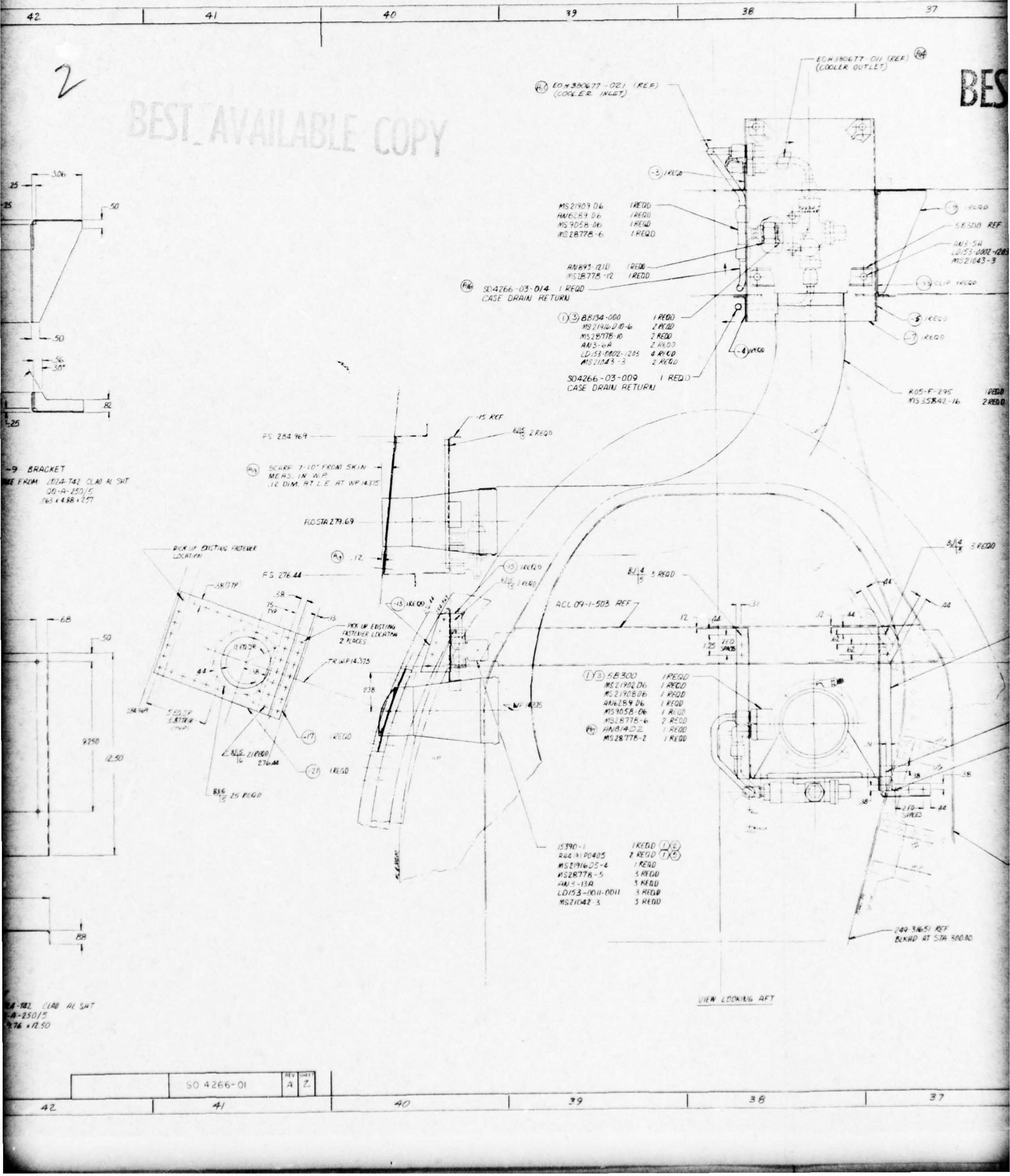
-3 ANGLE LH SHOWN
-4 RH OPP

MAKE FROM: 2024-T42 CLAD AL SHT
QQ-A-250/5
.063 x 2.44 x 9.31

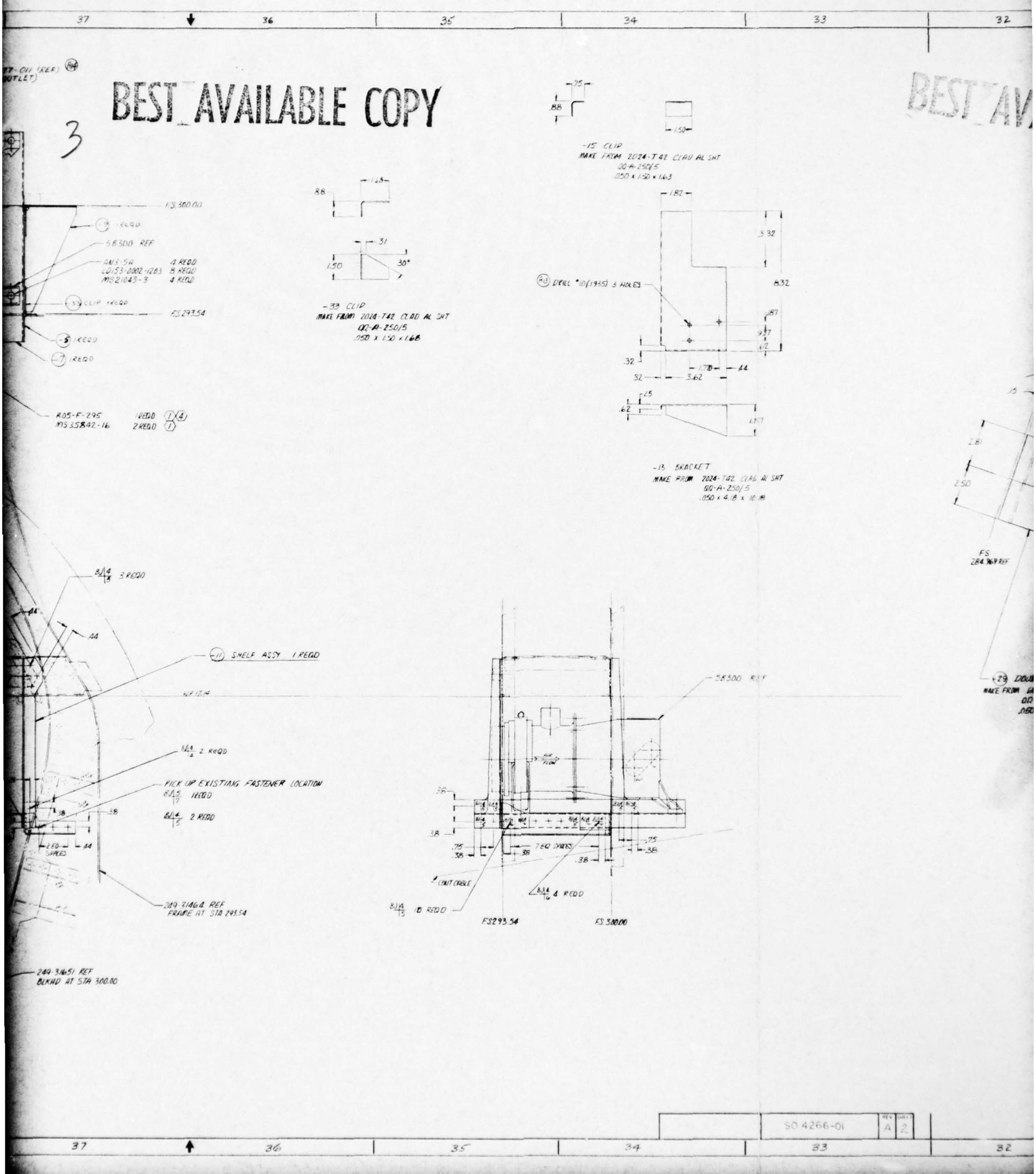


-7 SHELF
MAKE FROM: 2024-T42 CLAD AL SHT
QQ-A-250/5
.063 x 9.76 x 12.50

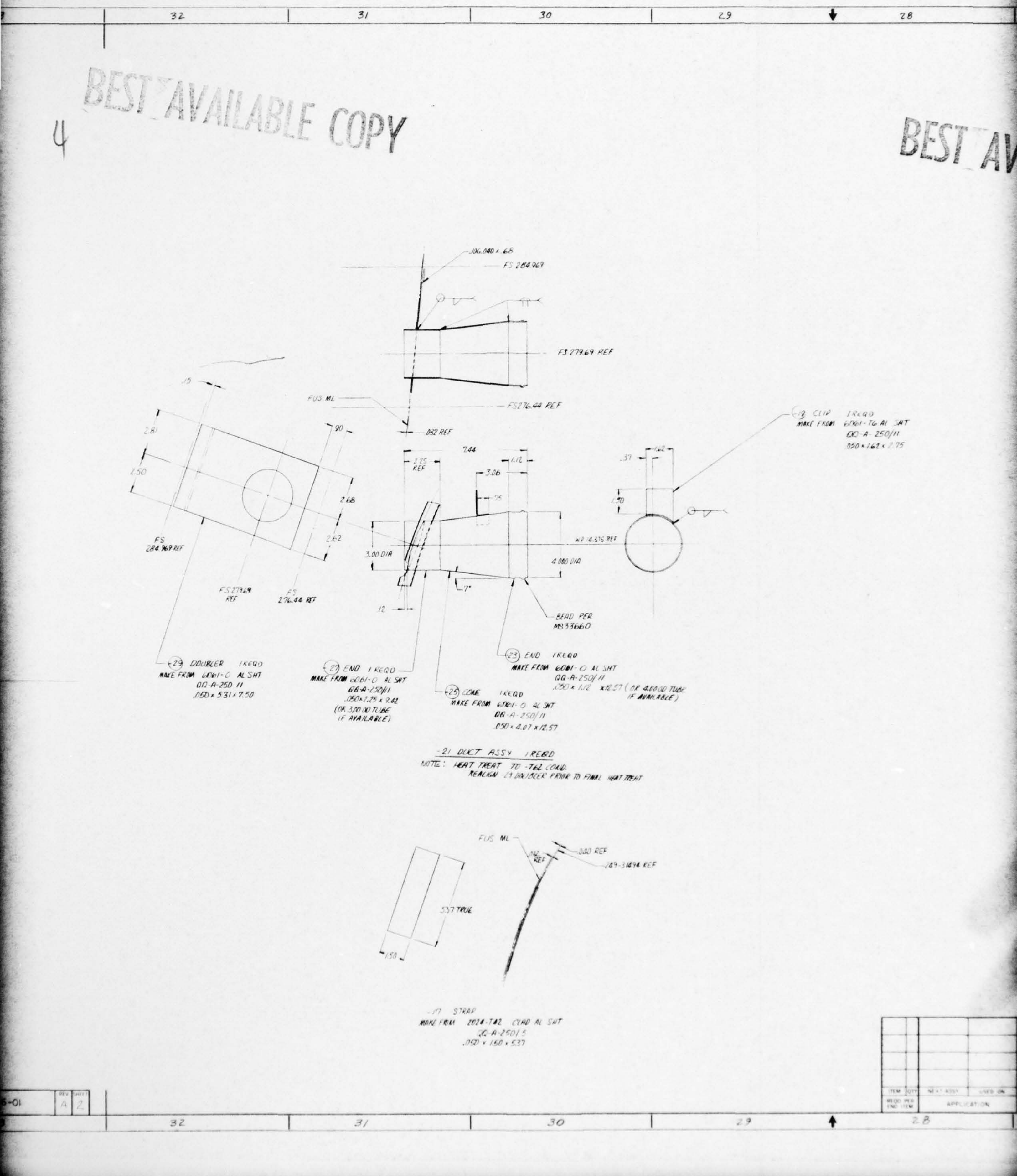
2



SO 4266-01	REV A	SHEET 2


37
36
35
34
33
32
3
FS 300.00
-9 1 REQD
58300 REF
AN3-5A 4 REQD
L0153-0002-1283 8 REQD
MS21043-3 4 REQD
-33 CLIP 1 REQD
FS 293.54
-5 1 REQD
-7 1 REQD
R05-F-295 1 REQD
MS35842-16 2 REQD
-33 CLIP
MAKE FROM 2024-T42 CLAD AL SHT
QQ-A-250/5
.050 x 1.50 x 1.68
-15 CLIP
MAKE FROM 2024-T42 CLAD AL SHT
QQ-A-250/5
.050 x 1.50 x 1.63
DRILL #10 (.1935) 3 HOLES
-13 BRACKET
MAKE FROM 2024-T42 CLAD AL SHT
QQ-A-250/5
.050 x 4.18 x 10.18
FS
284.969 REF
-29
MAKE FROM
3 REQD
-11 SHELF ASSY 1 REQD
2 REQD
PICK UP EXISTING FASTENER LOCATION
1 REQD
2 REQD
249-31464 REF
FRAME AT STA 293.54
249-31651 REF
BLKHD AT STA 300.00
58300 REF
7 EQ SPACES
CUT CABLE
10 REQD
4 REQD
FS 293.54
FS 300.00
SO 4266-01
A
2

4



32
31
30
29
28
.106.040 x .68
FS 284.969
FS 279.69 REF
FUS ML
FS276.44 REF
.052 REF
.15
2.81
2.50
.90
2.68
2.62
FS
284.969 REF
FS 279.69
REF
FS
276.44 REF
7.44
2.25
REF
1.12
3.06
.25
3.00 DIA
4.000 DIA
WP 14.375 REF
.12
7°
BEAD PER
MS33660
-19 CLIP 1 REQD
MAKE FROM 6061-T6 AL SHT
QQ-A-250/11
.050 x 2.62 x 2.75
.37
1.62
.50
-29 DOUBLER 1 REQD
MAKE FROM 6061-O AL SHT
QQ-A-250/11
.050 x 5.31 x 7.50
-27 END 1 REQD
MAKE FROM 6061-O AL SHT
QQ-A-250/11
.050 x 2.25 x 9.42
(OR 3.00 OD TUBE
IF AVAILABLE)
-25 CONE 1 REQD
MAKE FROM 6061-O AL SHT
QQ-A-250/11
.050 x 4.07 x 12.57
-23 END 1 REQD
MAKE FROM 6061-O AL SHT
QQ-A-250/11
.050 x 1.12 x 12.57 (OR 4.00 OD TUBE
IF AVAILABLE)
-21 DUCT ASSY 1 REQD
NOTE: HEAT TREAT TO -T62 COND.
REALIGN -29 DOUBLER PRIOR TO FINAL HEAT TREAT
FUS ML
.052
REF
.040 REF
289.31494 REF
5.37 TRUE
1.50
-17 STRAP
MAKE FROM 2024-T42 CLAD AL SHT
QQ-A-250/5
.050 x 1.50 x 5.37
5-01
REV
A
SHT
2
ITEM
QTY
NEXT ASSY
USED ON
REQD PER
END ITEM
APPLICATION

ZONE	LTR	DESCRIPTION	DATE	APPROVED
		1 MAY BE REWORKED 2 CANNOT BE REWORKED 3 RECORD CHANGE 4 NOW SHOP PRACTICE 5 PARTS MADE OK		
	A	SEE SHEET 1		

BEST AVAILABLE COPY

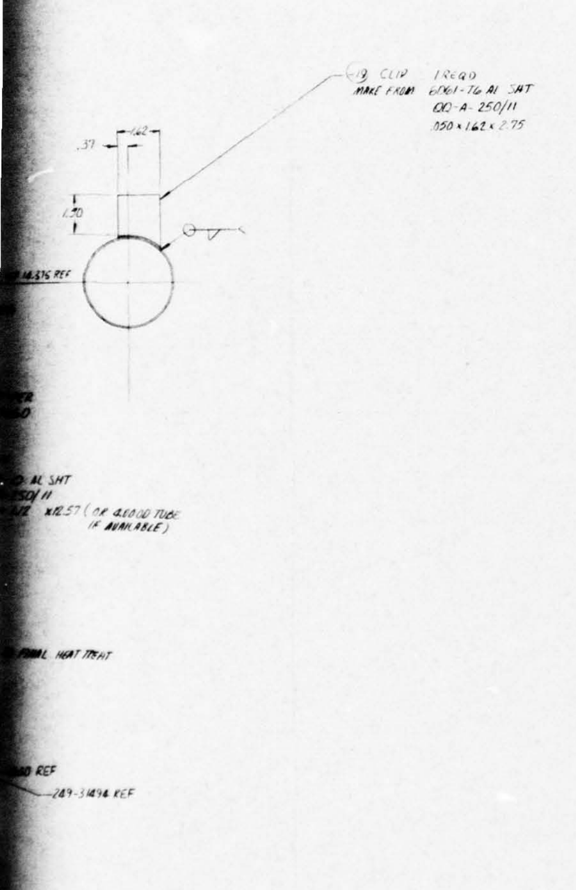


FIGURE 6 (CONT.)

5. RESISTOFLEX CORP, ROSELAND, N.J., 07068.
4. FOURNIER RUBBER & SUPPLY CO, 459 NO. HIGH ST, COLUMBUS, OHIO, 43215.
3. STANDARD-THOMSON CORP, WALTHAM, MASS.
2. STERER MANUFACTURING CO, COLORADO BLVD. L.A. CALIF. 90039.
1. PARTS TO BE FURNISHED BY ENGINEERING.

NOTES UNLESS OTHERWISE NOTED

FOR PARTS LIST SEE PL

UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES
MFG TOLERANCES ON
UNDIMENSIONED ± .03
XX (DECIMALS) ± .03
XXX (DECIMALS) ± .010
ANGLES ± 30'

Rockwell International Corporation
Columbus Aircraft Division

HYDRAULIC EQUIP INSTALLATION 8000 PSI SYSTEM FOR T-2C AIRCRAFT

SIZE J CODE IDENT NO 89372 S04266-01

SHEET 2 OF 2

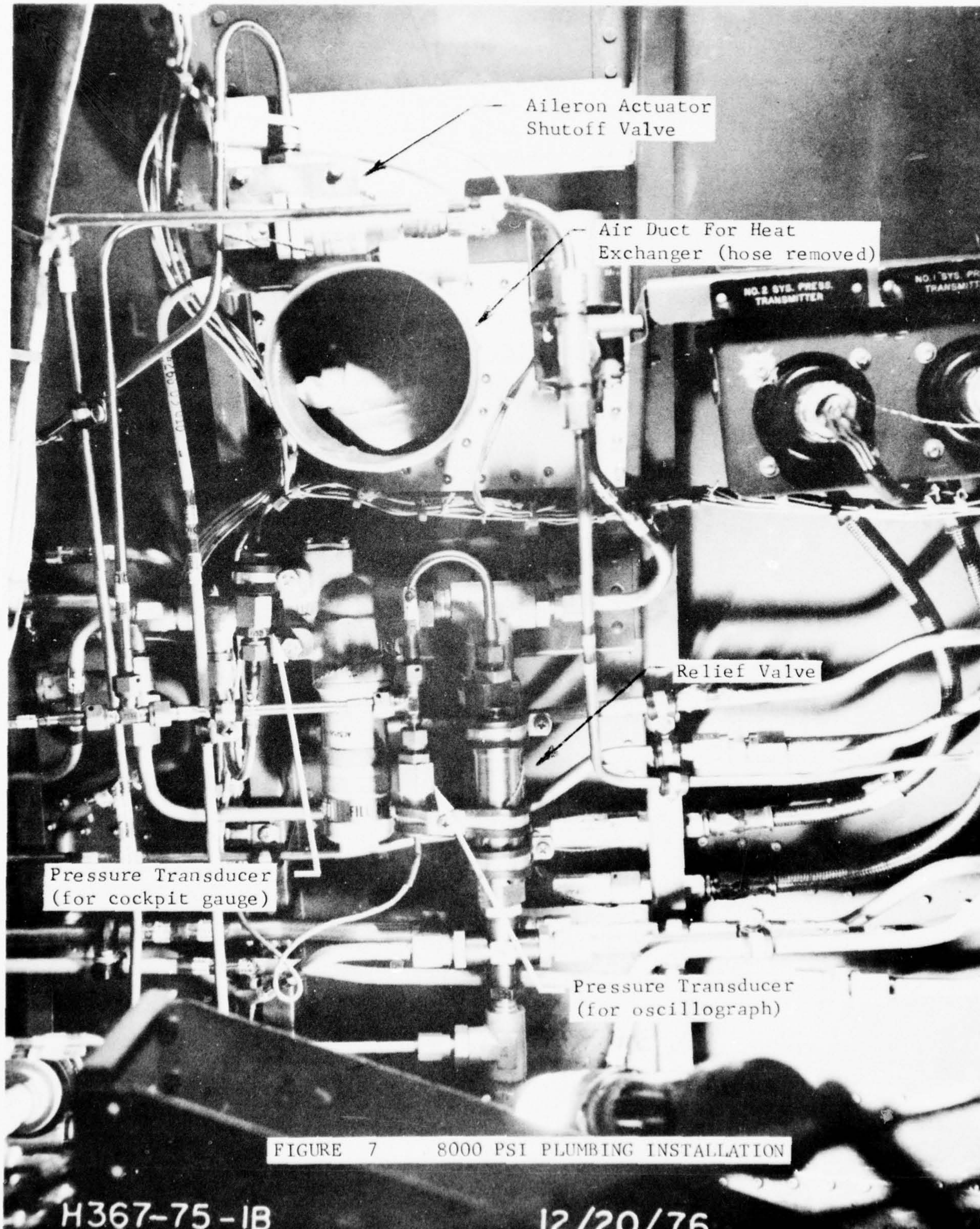


FIGURE 7 8000 PSI PLUMBING INSTALLATION

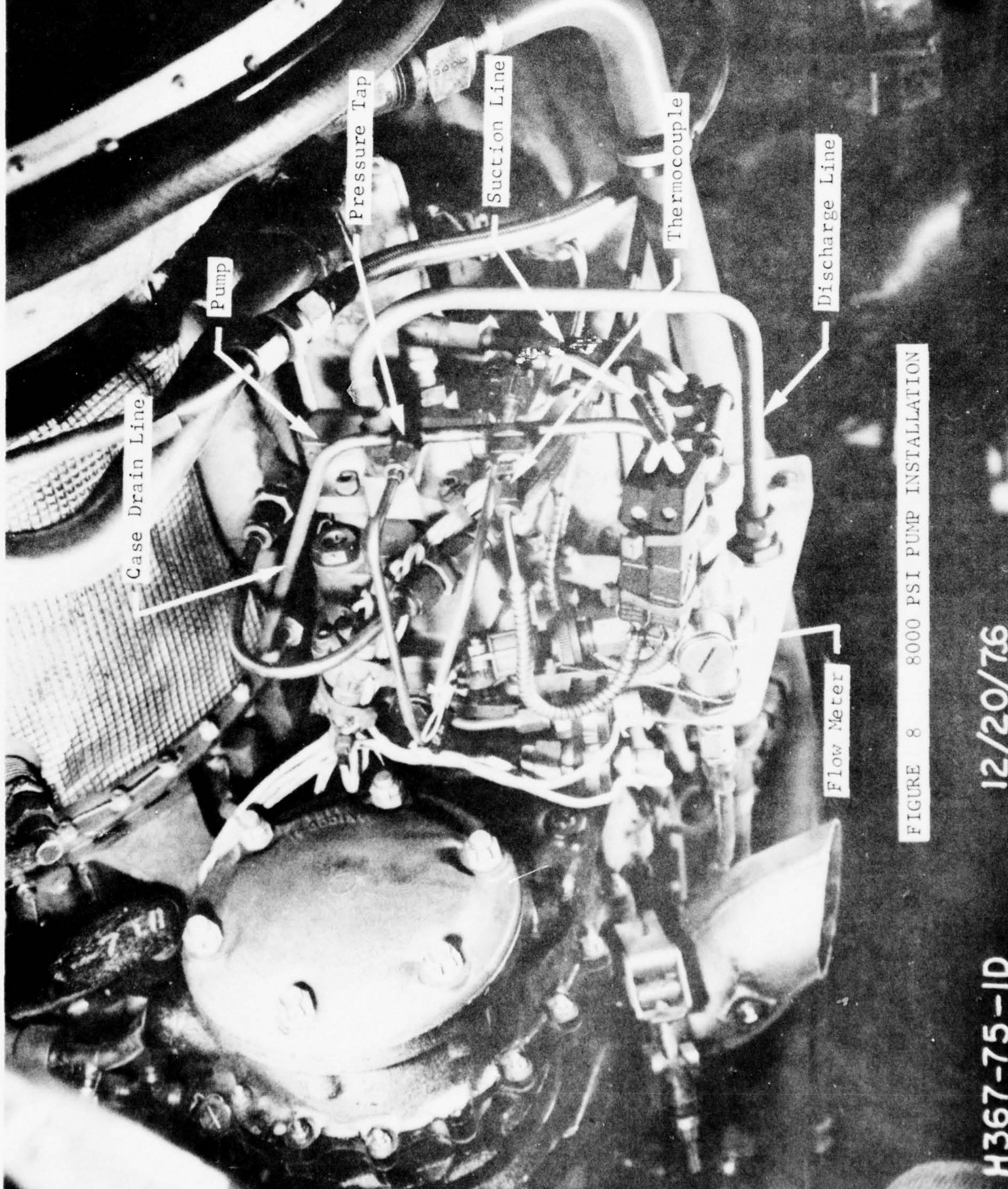


FIGURE 8 8000 PSI PUMP INSTALLATION

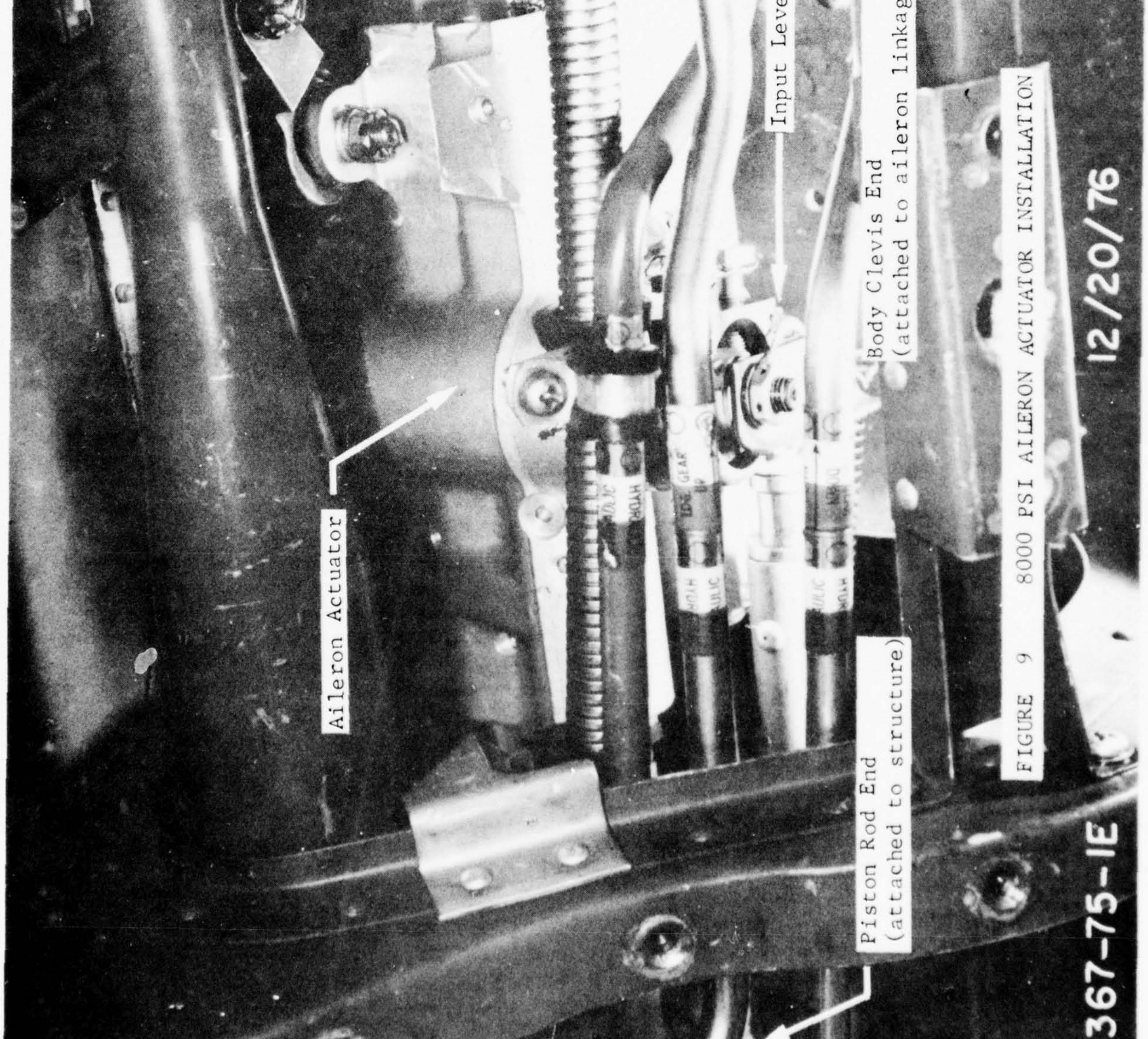


FIGURE 9 8000 PSI AILERON ACTUATOR INSTALLATION

3.2 INSTRUMENTATION

The bailed T-2C is equipped with several flight data acquisition systems. Two were used in the LHS program: (1) a 50 channel oscillograph recorder system; and (2) a 21 hole photo recorder system. The oscillograph system was located in the aft seat area, Figure 10; the photo recorder system was installed inside the nose, Figure 11.

Pilot instrumentation controls are located above the cockpit instrument panel and on the control stick, Figure 12. Data in the two recording systems is related by means correlator numbers printed on the photo recorder film, and correlator blips on the oscillograph film. A correlator counter is read by the pilot for reference purposes.

Existing instrumentation in the aircraft are listed below. Although several of these parameters were not directly applicable to the LHS program, they were retained in an active status.

OSCILLOGRAPH RECORDER	PHOTO RECORDER
1. OAT	1. Airspeed
2. Correlation	2. Altitude
3. Pilot's marker	3. Pilot's marker
4. Angle of pitch	4. Time
5. Angle of bank	5. Frame counter
6. Rate of roll	6. Angle of attack
7. Normal acceleration at CG	7. Angle of sideslip
8. Longitudinal stick position	8. Fuel used, L/R
9. Lateral stick position	9. EGT, L/R
10. Rudder position	10. RPM, L/R
11. L/R aileron position	11. Fuel temperature, L/R
12. Elevator position	

New instrumentation added specifically for the LHS program are listed on Table II. Operating range, accuracies, and response capabilities are also listed.

New equipment installed to permit the pilot to monitor the status of the 8000 psi system were:

- An indicator was provided for direct readout of system pressure downstream of the aileron actuator shutoff valve.
- An "oil hot" light was set to operate when hydraulic fluid in the 8000 psi pump suction line exceeded approximately +200°F.
- A switch was provided to operate the aileron actuator shutoff valve.

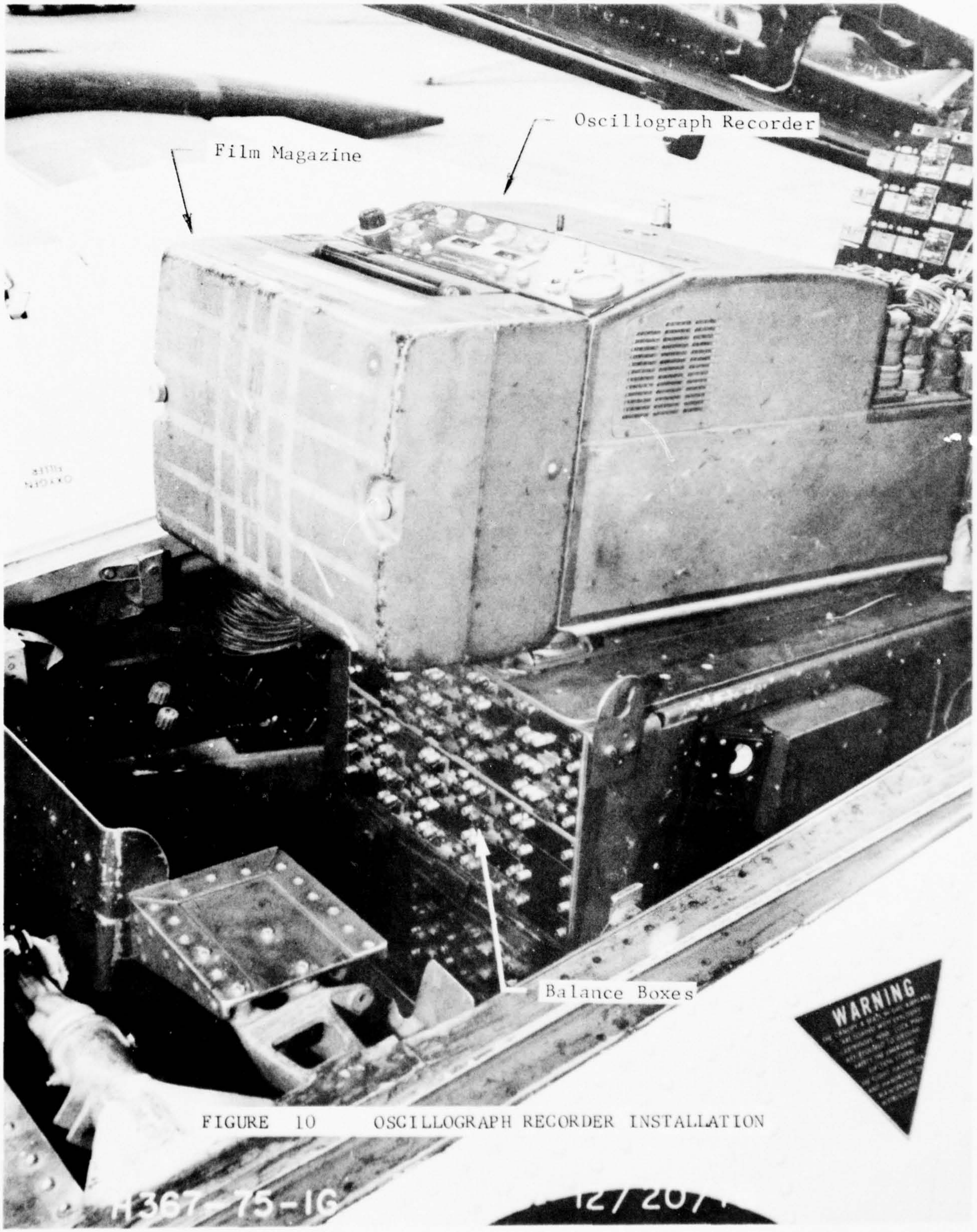


FIGURE 10 OSCILLOGRAPH RECORDER INSTALLATION

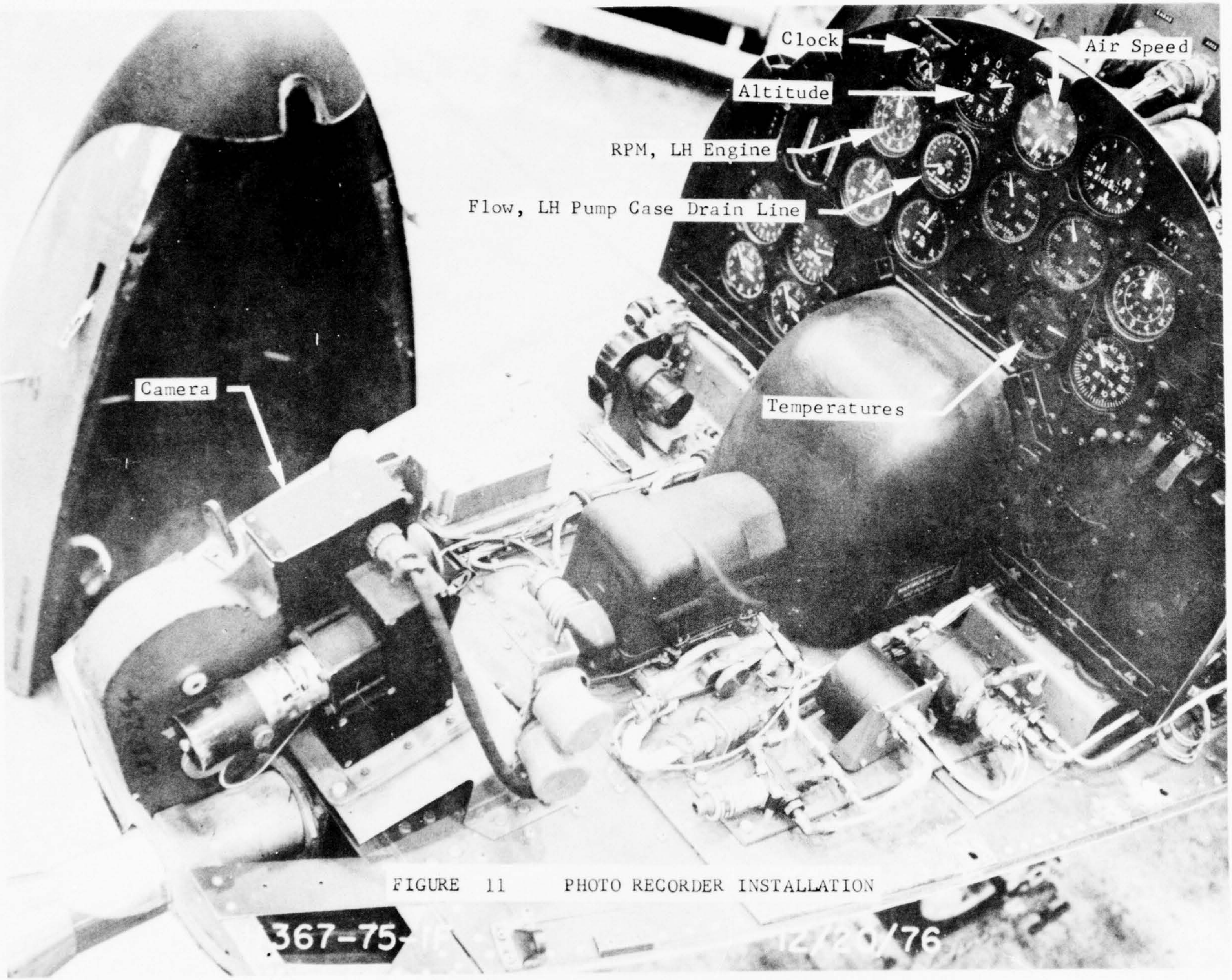


FIGURE 11 PHOTO RECORDER INSTALLATION

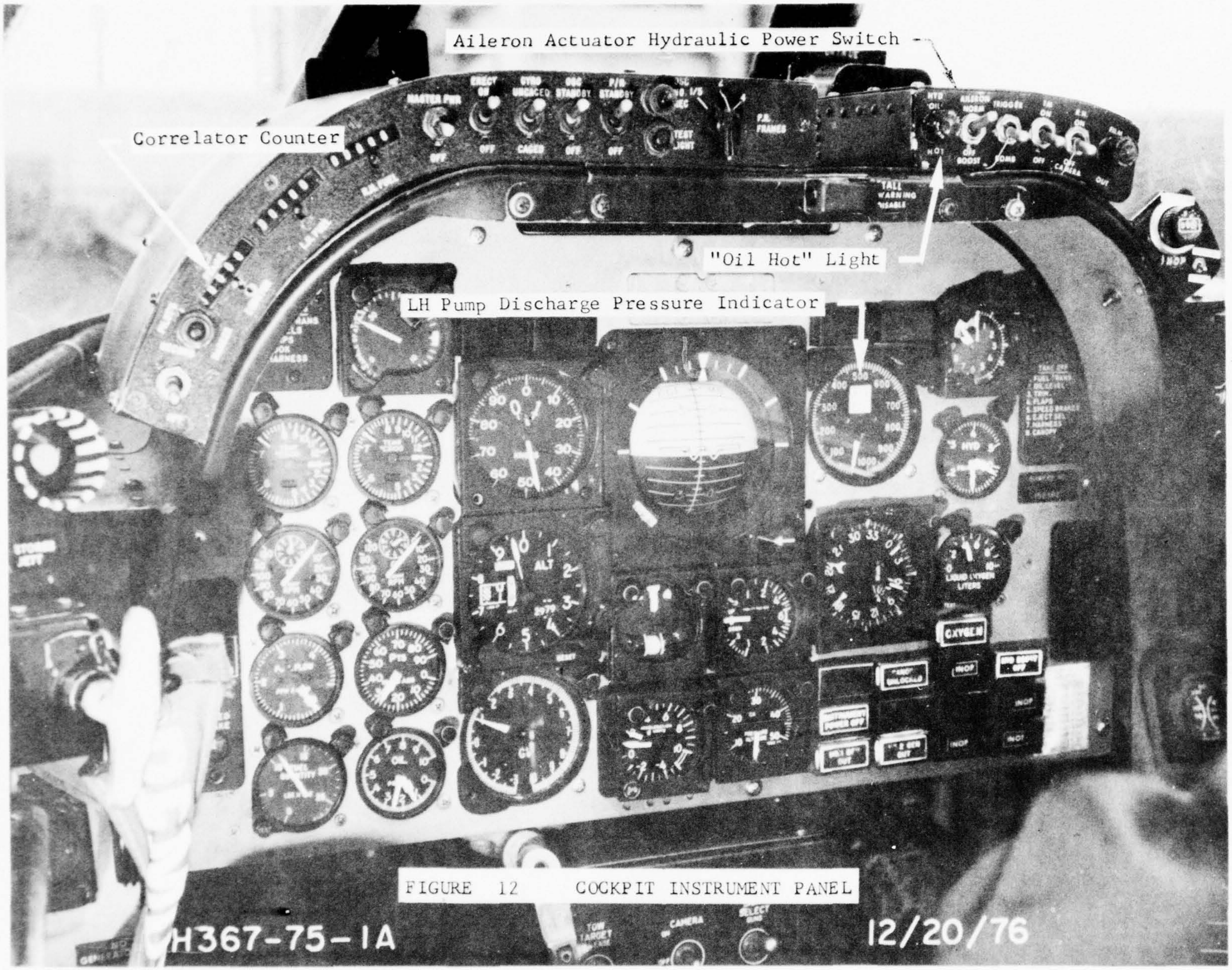


FIGURE 12 COCKPIT INSTRUMENT PANEL

TABLE II

LIST OF INSTRUMENTATION

	PARAMETER	TRANSDUCER	RANGE	ACCURACY	READOUT RESPONSE
	PHOTO RECORDER				
1.	Temp, aft fuselage bay air	TC	-20 to +160°F	±3°	2 Hz
2.	Temp, LH pump suction port	TC	0 to +240°F		
3.	Temp, LH pump case drain port	TC	+60 to +275°F		
4.	Temp, RH pump case drain port	TC	+60 to +275°F		
5.	Temp, heat exchanger inlet	TC	+60 to +275°F		
6.	Temp, heat exchanger outlet	TC	+60 to +275°F		
7.	Flow, LH pump case drain	PWFM	0 to 1.5 gpm		
	OSCILLOGRAPH RECORDER				
1.	Press, LH pump suction port	SGPT	0 to 50 PSIA	±1%	60 Hz
2.	Press, LH pump case drain port	SGPT	0 to 100 PSIA		
3.	Press, LH pump discharge line	SGPT	0 to 10,000 PSI *		135 Hz

NOMENCLATURE:

TC Thermocouple
SGPT Strain gage pressure transducer, Standard Controls M/N 211-35-000 *
PWFM Paddle Wheel Flow Meter, Flow Technology M/N FTM-10-LB

4.0 PREFLIGHT CHECKS

4.1 HANGAR TESTS

Hydraulic Fluid Contamination

The hydraulic system originally contained MIL-H-5606 (red) fluid. This was removed and replaced with MIL-H-83282 (amber) "less flammable" fluid. The changeover was accomplished by flushing the system with MIL-H-83282 until a satisfactory fluid color was attained. Procedure details are given in Appendix A. All sub-systems were cycled in a planned sequence to achieve optimum flushing action with minimum introduction of air. A service ground cart supplied the MIL-H-83282 fluid and pressure necessary for the flushing operation.

Although the system was flushed thoroughly, it was not possible to remove all traces of MIL-H-5606. The amount of MIL-H-5606 remaining was estimated to be about 6%. This determination was made with a Bausch & Lomb optical colorimeter.

Particulate contamination was based on a 100 cc sample taken from the return line, reference Figure 4. Particulate size and quantity were measured with a HIAC automatic particle counter. The results are given below:

	MICRON SIZE RANGE				
	5-10	10-25	25-50	50-100	100+
Maximum Number (Class 5)	87,000	21,400	3130	430	41
T-2C BuNo. 152382 (after flushing)	23,438	2,486	106	12	0

NAVAIR 01-1A-17 Class 5 requirements are applicable to the T-2C. The contamination level measured was equivalent to a Class 3.

A patch test was run on fluid poured from the filter bowl in the 8000 psi pump case drain line. A significant number of large, grey colored metallic chips were observed. This was considered to be normal cleanup for a newly fabricated system.

Leak Checks

The 8000 psi portion of the test installation was pressurized with a 0.2 gpm, 10,000 psi power supply containing an adjustable relief valve, Appendix A. The aileron actuator was operated at 8000 psi; no external leakage was found. Pressure was increased sufficiently to operate the system relief valve (8800 to 9000 psi). No leakage or malfunctions were observed.

The 3000 psi system was pressurized with a service ground cart and all subsystems were operated. Minor leaks were found and corrected.

System Operation

The aileron system was operated at 8000 psi by hangar personnel familiar with the stick feel of the 3000 psi aileron system. There was no significant difference between the operation or feel of the two systems.

The 3000 psi subsystems were powered. Operation of the landing gear, elevator actuator, speed brakes, and arresting hook was normal.

Heat Exchanger Tests

The heat exchanger blower motor was energized with 400 cycle, 3 phase, 110 volts; operation was satisfactory. A suction of 4.25 in. of water below atmospheric pressure was measured inside the blower inlet duct near the opening on the side of the aircraft. Air pressure buildup within the fuselage (all access doors closed) was determined to be 0.01 in. of water above atmospheric. The suction and fuselage pressure values were satisfactory.

Instrumentation Checks

8000 psi was applied to the test installation. The cockpit pressure gage was observed to read 7900 psi with hydraulic power switched "on" and zero pressure with power "off". This test confirmed satisfactory operation of the pressure indicator and the shutoff valve hookup.

Conventional instrumentation procedures were followed in calibrating and checking out the 8000 psi pressure transducer, case drain line flow meter, and thermocouples.

4.2 RAMP TESTS

Resonance Search

This test was conducted to determine if destructive vibrations or hydraulic resonances occur in the 8000 psi system under normal operating conditions. The engine access, hydraulic reservoir, and plumbing compartment doors were open to permit visual inspection of hydraulic system lines during the resonance search. Procedure details are given in Appendix A.

Both engines were started and run at 75% power to warm up the hydraulic fluid. The heat exchanger blower was turned off to decrease warm-up time. Outside air temperature was +43°F. After 15 minutes of running, fluid in the 8000 psi pump suction line reached +142°F. Both engines were shutdown. The instrumentation recorders were turned on. With hydraulic power switched "on" the aileron actuator, engine No. 1 was started and speed was slowly increased from 48% (idle) to 100% then from 100% to 48% and shut down. The recorders were then turned off. This procedure was repeated with hydraulic power "off" the aileron actuator.

No destructive plumbing vibrations were observed during the resonance search. Examination of the oscillographic data disclosed no hydraulic resonance at any engine speed. The maximum pressure oscillations recorded were less than 200 psi peak-to-peak. The test installation was considered to be unusually quiet with respect to pressure fluctuations normally associated with pump/system interaction. Composite oscillographic records of the resonance search are presented on Figure 13.

Pressure Surge Test

Engine No. 1 was started and run up to a power setting of 94% (cruise). The recorders were turned on. The aileron actuator hydraulic power switch was then operated "on" and "off" three times. With the switch "on", the ailerons were operated full up to full down three times as fast as possible. Peak pressures generated by these tests were 8800 psi when switching to power "off", and 8100 psi during fast operation of the ailerons, Figures 14 and 15. These surges were well below the 120% maximum allowable (9600 psi), Reference 4.

Simulated Flight

This test was conducted to simulate a one hour flight from takeoff to landing, and provide a means to final check hydraulic system operation and instrumentation. Engine speed and pilot stick inputs were varied to simulate actual flight. Test details are given in Appendix A.

The heat exchanger blower was "on" and all access doors were closed for the hour long run. Air temperatures in the aft fuselage bay (fore and aft) were monitored with a potentiometer external to the aircraft. Both engines and both hydraulic systems were run. A summary of the "flight" is given below:

Description	Engine Speed, % MRT	Duration, Min.
System Checkout & Taxi out	48%	10
Takeoff	100%	4
Cruise & Maneuver	80 to 100%	36
Landing & Taxi In	48%	10
Temperature Soak-out	0	20

Outside air temperature was +44°F; aft fuselage bay air averaged +70 to 80°F during the run. Hydraulic fluid temperatures peaked just prior to the 80% MRT portion of the "flight" when the 8000 psi pump suction temperature reached +141°F and the case drain temperature +200°F. The temperature soakout produced only decreasing temperatures. Photo-recorder and oscillograph data are summarized on page 31.

Pressure surges resulting from rapid lateral system operation were under 120 psi; pump ripple was approximately 160 psi peak-to-peak. These values were considered to be very good.

Pump discharge pressure, as indicated by the oscillograph trace and cockpit gauge, was over 8000 psi; this was an erroneous indication caused by instrumentation drift. The pressure transducers (15,000 psi, Standard Controls M/N 211-35-000) were suspected, because stringent temperature compensation requirements were not imposed -- for economic reasons -- during their procurement seven years ago.

NOTE: Pressure transducer located upstream of aileron actuator shut-off valve

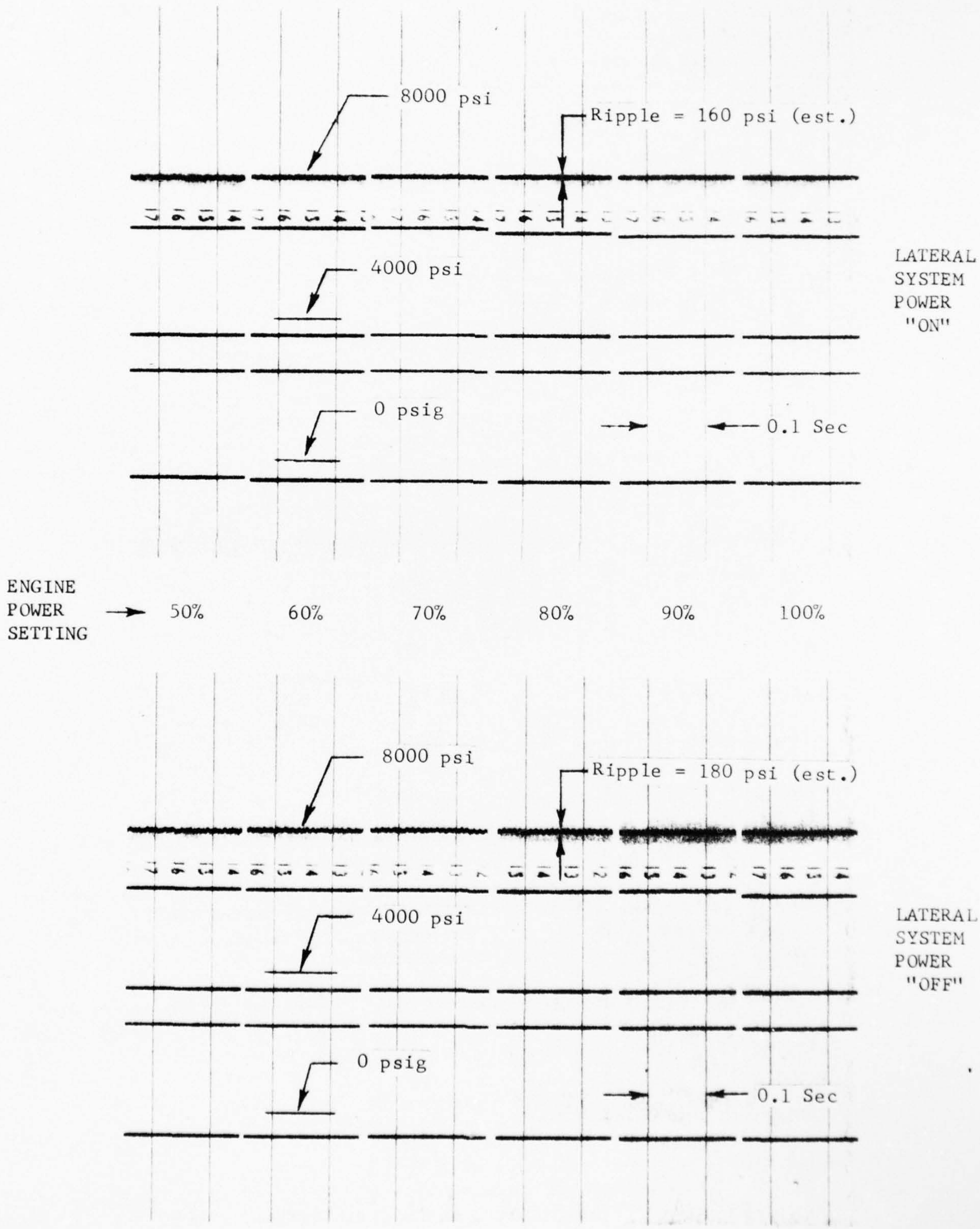


FIGURE 13 HYDRAULIC RESONANCE SEARCH

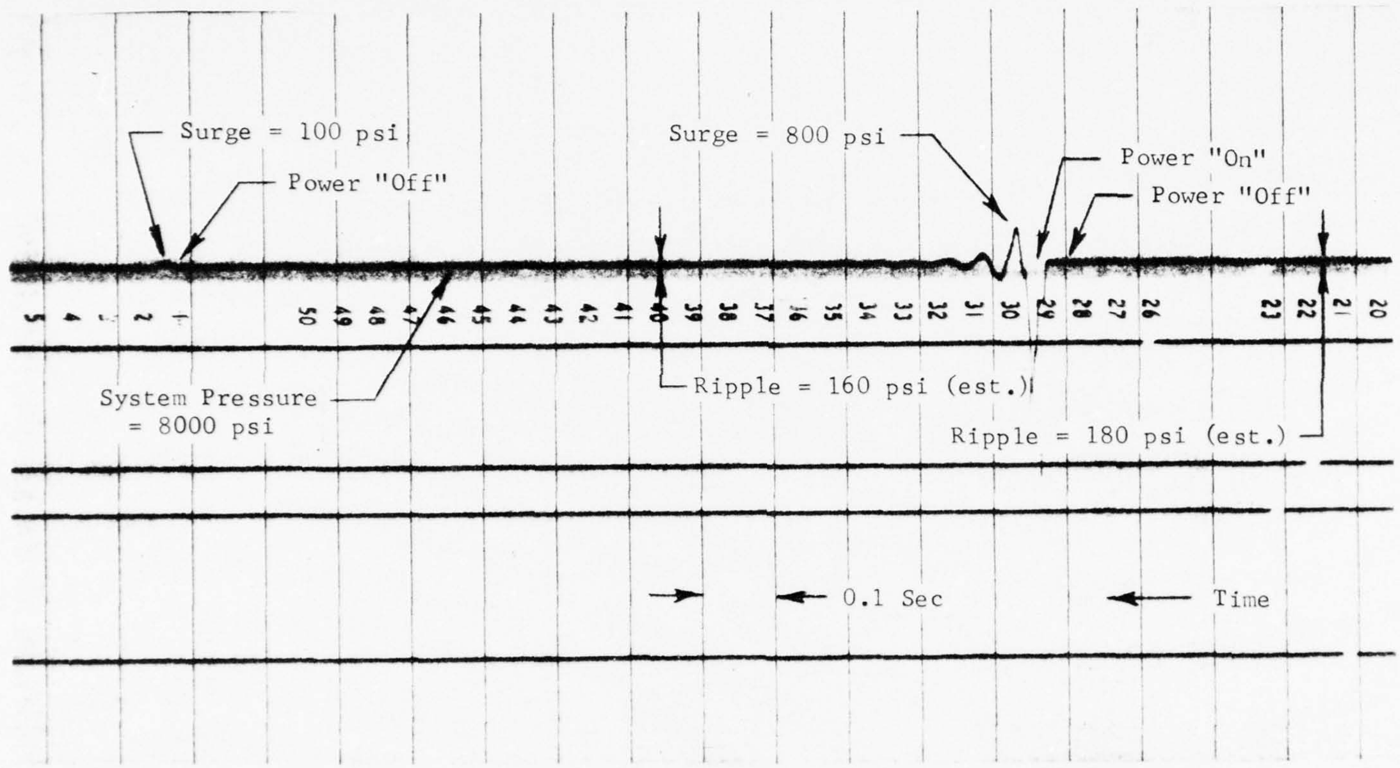


FIGURE 14 PRESSURE SURGE, LATERAL SYSTEM POWER OFF-ON

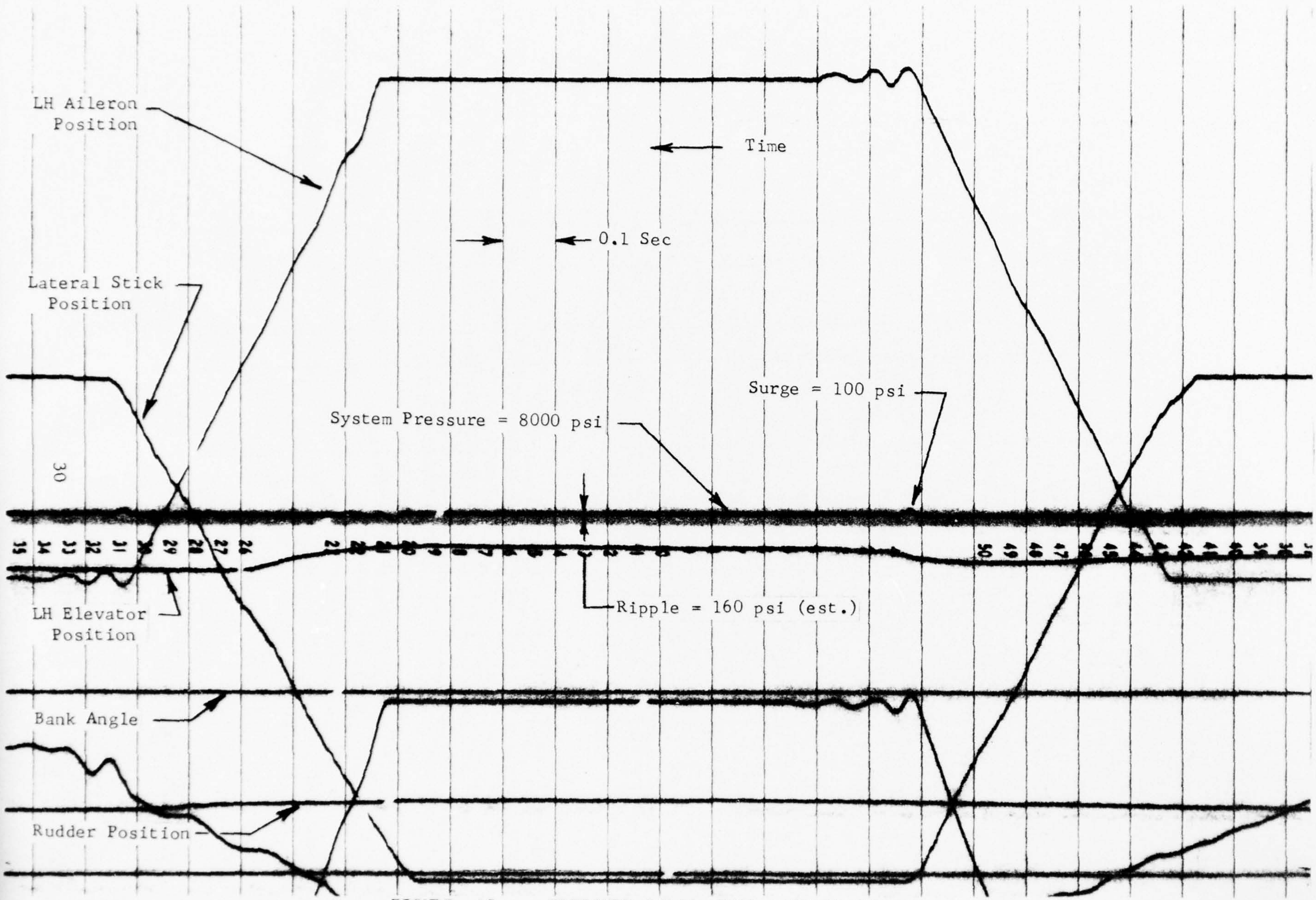


FIGURE 15 PRESSURE SURGE, FULL LATERAL INPUT

A/C T2C #1
PILOT CREW CHIEF DATE 12-6-76 FILM TYPE PR READ BY RKH
NAV. FLT. NO. OSC NO 1 WRITTEN BY CALIB BY TEST/MANEUVER 60 MIN. GROUND RUN
PAGE 1 OF 1

RUN	CORR	TIME	1 CLOCK	2 ALT FT	3 A/S KTS	5 L/H RPM REVS	6 L/H PUMP CASE DRAIN GPM	14-1 AFT COMP. AIR L/H °F	14-2 SUCT. PORT L/H °F	14-3 CASE DRAIN PORT L/H °F	14-4 CASE DRAIN PORT R/H °F	14-5 HEAT EX. IN PORT °F	14-6 HEAT EX. OUT PORT °F	5 OAT °F	18 SUCT. PORT L/H PSIG	P-P PSIG	19 DISCH PORT L/H PSIG	P-P PSIG	SURGE ΔPSI	20 CASE DRAIN L/H PSIG	P-P PSIG	
														F=2.03	F=3.33 K=21.74		F=3.97 K=3969			F=2.12 K=[illegible]		
	82		1351	–	0	[illegible] 7952	.29	56 57	64 65	105 110	53 54	67 68	50 51	2.24 +44	[illegible] 0		[illegible] 8176			47 41	← RAW DATA ← REDUCED DATA	ENGINE START
	153		1401	–	0	[illegible] 7736	.50 .49	54 55	106 108	168 170	137 139	145 147	128 130	2.27 45	3.46 2	.75	6.04 8216	.63 200	.63 120	47 41	.44	48% POWER (IDLE) (TAXI)
	204		1405	–	0	7650 16482	.63 .62	59 60	119 121	180 182	186 188	170 172	145 147	2.29 46	3.56 4.6		6.07 8334			5.14 52		100% POWER (TAKE-OFF)
	250		1410	–	0	[illegible] 14970	.70 .67	66 67	129 131	190 192	184 186	177 179	150 152	2.29 46	3.67 7.0		6.08 8374	.02 180	110	[illegible] 50		90% POWER
	283		1413	–	0	[illegible] 16459	.70 .67	67 68	132 134	194 196	195 197	183 185	154 156	2.29 46	3.64 6.3		6.19 8414			[illegible] 50		100% POWER
	309		1418	–	0	[illegible] 14948	.72 .69	72 73	137 139	194 196	188 190	183 185	153 155	2.31 49	3.60 5.4		6.19 8414			[illegible] 48		90% POWER
	334		1420	–	0	[illegible] 16480	.72 .69	73 74	136 138	198 200	198 200	188 190	157 159	2.31 49	3.60 5.4		6.19 8414			5.14 52		100% POWER
	360		1426	–	0	[illegible] 14970	.73 .70	75 76	141 143	[illegible] 202	194 196	187 189	156 158	2.27 45	3.60 5.4		[illegible] 8454			[illegible] 49		90% POWER
	386		1432	–	0	[illegible] 13306	.71 .68	77 78	[illegible] 141	197 199	179 181	[illegible] 180	154 156	[illegible] 47	3.60 5.4		6.11 8494			[illegible] 50		80% POWER
	413		1441	–	0	[illegible] 7952	[illegible] .60	75 76	130 132	184 186	157 159	171 173	149 151	2.30 47	[illegible] 5.4		[illegible] 8414			[illegible] 42		48% POWER (IDLE)
	517		1443	–	0	0	0	75 76	125 127	167 169	143 145	155 157	138 140	47	3.61 5.6		[illegible] 278			3.41 7		SHUT DOWN
	542		1444					75 76	121 122	159 161	137 139	147 149	129 131	46								TEMP SOAK-OUT
	568		1453					66 67	89 91	99 101	96 98	70 71	61 62	46								

DATA SHEET DEPT. FORM NO. 383-V-3 NOTE: ABOVE DATA TAKEN NEAR THE END OF EACH POWER SETTING.

5.0 FLIGHT TESTS

5.1 FLIGHT PLAN

The primary objective was to provide further evidence of the feasibility of the LHS concept by flight testing an 8000 psi hydraulic control system. Demonstration of flying qualities was not part of the program, however pilot comments were encouraged.

Ten flight hours were expected to be sufficient to attain a measure of confidence in LHS performance and reliability. Thus, secondary objectives were to show: (1) the endurance capability of the 8000 psi system, although not thoroughly proven at this time, was satisfactory as predicted by prior analyses and laboratory testing; and (2) that pilot reaction toward the system was favorable.

The flight plan was designed to determine lateral control characteristics at several altitudes up to 30,000 ft. and various speeds up to 400 knots. The first two flights were dedicated to confirming satisfactory operation. Subsequent flights were scheduled to evaluate system endurance while accumulating 10 flight hours. Several pilots were utilized to permit differing opinions on performance. Flight plan details are given in Appendix A.

5.2 RESULTS

The test flights and flight durations are summarized on Table III. Flight 1 was terminated approximately midway (at 15,000 ft.) when the left engine compressor fire warning light illuminated; a safe landing was made. An investigation resulted in the conclusion that hot air leaks caused the false indication. Two seals and two check valves were replaced in the T-2C heat and vent system, and a ground run was made with satisfactory results. Flight 2 was terminated when the same fire warning light came on at 16,000 ft. during the initial climb to 20,000 ft. Further ground checks disclosed an intermittent electrical short in the fire warning system. This was corrected and all subsequent flights were incident free. (Tasks originally scheduled for Flight 2 were shifted to Flight 3.)

Four pilots participated in the flight program. Reports were written by each pilot detailing the flights. Additional comments were made verbally during flight de-briefings. All agreed that performance of the 8000 psi test installation was completely satisfactory; no malfunctions occurred. Each pilot stated that operation of the 8000 psi system was very similar to the T-2C 3000 psi lateral system, and that any differences noted were minor -- well within tolerances for the 3000 psi system. General comments made by the pilots regarding the 8000 psi system were:

- Lateral control system operation was normal
- Power-on breakout forces were low
- System pressure was stable even with large stick inputs
- The system was slightly more responsive around neutral
- The lateral control force gradient was slightly steeper
- System pressure indication decreased slightly with altitude
- Power-off forces were slightly higher
- Engine windmilling could provide sufficent pressure to operate the ailerons

Instrumentation drift caused the cockpit gauge and the oscillograph trace to indicate system pressures slightly below 8000 psi. Fluid and air temperatures were lower during the flights than during the ground runs when the drift was upward, reference Section 4.2.

The T-2C lateral control system artificial feel bungee was responsible for the slightly higher lateral force gradient noted by the pilots. The bungee force was measured after completion of flight testing and found to be 239 lb. at 2.1 in. deflection; the drawing tolerance was 221 $\pm$ 18 lb. at 2.1 in.

Flight test data are given on pages 35, 36, and 37. Case drain fluid temperatures of both the 3000 psi and 8000 psi pumps were generally less than +190°F and within 10°F of each other. Pump inlet fluid temperatures were in the range of +100 to +130°F. Fluid temperature decrease through the heat exchanger averaged 20 to 25°F. All fluid temperatures were considered to be nominal.

Internal leakage of the 8000 psi pump depended on operating conditions and generally ranged from 0.50 to 0.69 gpm. These values agree with those obtained in the laboratory, Reference 8.

Oscillograph data covering various flight maneuvers and altitudes are presented in Figures 16 through 21. The maximum pressure surge occurred when lateral system power was switched from "off" to "on"; the pressure overshoot was 800 psi. The maximum surge observed during lateral system "power on" operation was 120 psi. These pressure surges were well below the 1600 psi (120%) maximum allowable, Reference 4.

Fluid particulate contamination decreased as flight time was accumulated, and after 10.3 flight hours was equivalent to a NAVAIR Class 2, page 44 and Figure 22. This low level of contamination was evidence of minimal pump wear and excellent fluid lubricity.

There was no external leakage at any plumbing joint in the 8000 psi system. Except for normal slight wetting, there was no external leakage around the 8000 psi pump shaft seal or the aileron actuator piston rod seal. No leakage occurred at the 8000 psi hoses.

TABLE III

LHS OPERATING TIME

LHS FLIGHT	DESCRIPTION	PILOT	TIME, HRS GROUND	FLIGHT	REMARKS
	Ground Run	--	0.3	--	Initial run-up stopped due to leak in 3000 psi system
	Ground Run	--	0.6	--	Preliminary resonance survey
	Ground Run	--	1.3	--	Resonance survey, pressure surge test, and simulated flight
1	T-2C Flt #599	Cockburn	0.1	0.6	Flight terminated due to fire warning light
	Ground Run	--	0.6	--	Checkout test to find cause of false fire warning
	Ground Run	--	0.4	--	Test to verify fix
2	T-2C Flt #600	Lane	0.1	0.3	Flight terminated due to fire warning light
	Ground Run	--	0.2	--	Test to verify fix
3	T-2C Flt #601	Lane	0.1	1.1	Check out LHS operating characteristics
4	T-2C Flt #602	Cockburn	0.1	1.5	System Endurance Evaluation
5	T-2C Flt #603	Cockburn	0.1	1.2	System Endurance Evaluation
6	T-2C Flt #604	Cockburn	0.4	1.1	System Endurance Evaluation
7	T-2C Flt #605	Wenzell	0.1	1.5	System Endurance Evaluation
8	T-2C Flt #606	Gillespie	0.1	1.5	System Endurance Evaluation
9	T-2C Flt #607	Wenzell	0.1	1.5	System Endurance Evaluation
*	T-2C Flt #608	Cockburn	0.1	.4	Transponder performance test
*	T-2C Flt #609	Cockburn	0.1	.8	Transponder performance test
		Totals	4.8	11.5	

*These flights were made after completion of LHS flight testing, but before removal of the 8000 psi test installation and restoration of the 3000 psi lateral control system.

A/C T2C #1 DATE 12-13-76 ☑FILM TYPE PR READ BY ☐ TEST/MANEUVER LHS FLT F3

PILOT LANS FLT. NO. 601 ☐OSC NO 1 WRITTEN BY CALIB BY

NAV

RUN	CORR	TIME	1	2	3	5	6	14-1	14-2	14-3	14-4	14-5	14-6	5	18		19		20		
			CLOCK	ALT	A/S	L/H RPM			SUCT. PORT					OAT	SUCT. PORT	P-P	OUT. PORT	P-P	CASE DRAIN	P-P	
				FT	KTS	REVS	GPM	°F	°F	°F	°F	°F	°F	°F	PSIG	PSIG	PSIG	PSIG	PSIG	PSIG	
2	150		45	5905	274.0	16530	.590	38	100	169	171	148	129	38.1	18.6	6.6	8057	—	55.1	14.4	← RAW DATA ← REDUCED DATA CLIMB
3	210		44.5	8440	196.5	13951	.560	38	103	166	163	146	126	31.2	18.8	8.8	8057	179	55.1	13.1	LATERAL CONTROL POWER OFF CHECK
	223																8811				
4	285		15	20440	315.0	16411	.650	33	113	187	186	164	139	30.3	16.9	8.8	8057	—	55.9	13.1	LEVEL MRT
5	350		7.5	[illegible]	237.5	12128	.600	33	112	183	181	161	142	25.3	11.4	8.8	8057	—	47.6	7.8	IDLE
	380		12	20070	[illegible]	16411	.625	32	110	181	178	158	135	24.2	16.4	8.8	—	—	56.4	11.8	
6	415		[illegible]	20270	324.5			32	111	184	183	161	137	33.1	17.5	8.8	8017	—	55.9	13.4	½ LAT. CONTROL 60°–60° ROLLS VMAX MRT
7	500		35.5	20640	317	16411	.645	34	107	181	183	157	135	32.6	17.5	8.8	8057	—	55.9	13.4	FULL LAT CONTROLS 60°–60°, 360° ROLLS VMAX MRT
8	610		55	25645	300	16293	.615	22	110	185	183	160	138	10.4	15.3	8.8	8017	-	53.3	9.1	LEVEL MRT
9	680		45	25635	285	12581	.600	21	110	181	180	153	138	6.5	9.9	5.5	7978		46.8	9.1	IDLE
10	755		15.5	25270	308.5	16304	.645	19	109	183	181	158	139	13.7	15.3	6.6	7938		55.9	7.8	½ LAT. CONTROL 60°–60° ROLLS VMAX MRT
11	810			24845	316.5	16304	.650	18	109	181	181	156	138	16.5	14.2	6.6	7938		54.6	7.8	FULL LAT. CONTROL 60°–60° ROLLS VMAX MRT

DATA SHEET DEPT. FORM NO. 383-V-3

A/C T2C #1 DATE 12-13-76 ☑ FILM TYPE PR READ BY 4H TEST/MANEUVER LHS FLT #3
PILOT LANE FLT. NO. 601 ☑ OSC NO 1 WRITTEN BY CALIB BY
NAV. PAGE 2 OF 2

RUN	CORR	TIME	1	2	3	5	6	14-1	14-2	14-3	14-4	14-5	14-6	5	18		19		20		
			CLOCK	ALT	A/S									OAT		P-P		P-P		P-P	
				FT	KTS	RPM	GPM	°F	°F	°F	°F	°F	°F	°F	PSIG	PSIG	PSIG		PSIG	PSIG	
12	890		3:46 35	35525	303.5	1634	.645	19	107	183	181	158	139	10.4	13.1	6.6	7938	—	53.3	7.8	FULL LAT. CONTROLS 360° ROLLS VMAX MRT
13	980		3:46 51	30760	275	1659	.635	0	111	183	182	158	144	-12.4	11.0	8.8	7878		49.4	7.8	LEVEL FLT MRT
14	1050		3:47 26.5	30590	264	1602	.645	-1	110	181	178	156	143	-15.7	8.1	8.8	7859		49.7	7.8	IDLE
15	1120		3:49 21	30090	284	16120	.645	-2	112	184	181	158	145	-6.3	12.7	8.8	7857		53.3	7.8	1/2 LAT CONTROL 60°-60° ROLLS Vmax MRT
16	1180		3:52 40	29890	282.5	16131	.635	-4	110	187	181	158	146	-7.4	12.5	8.8	7857		50.7	7.8	FULL LAT CONTROL 60°-60° ROLLS Vmax MRT
17	1250		3:53 18	30630	271.0	16120	.650	-3	—	183	181	158	145	-12.9	13.1	8.8	7878		50.7	9.1	
18	1350		3:55 5	30710	274.5	16196	.615	-5	108	183	181	156	145	-13.5	12.1	8.8	7660		50.7	9.1	FULL LAT CONTROLS 360° ROLLS V MAX MRT
19	1470		4:02	15810	360	16,422	.625	33	100	175	177	152	131	55.2	19.1	5.5	7700		57.2	6.5	FULL LAT CONTROL 60°-60° ROLLS Vmax MRT
20	1530		4:03	15720	364.0	16,466	.635	42	104	176	179	154	131	56.4	✓	5.5	✓		57.2	7.8	
21	1690		4:07 40	11005	389.0	16457	.645	55	108	181	183	159	136	67.5	18.2	7.7	7740		59.6	9.1	
22	1944		4:22 16	330	42	8043	.410	38	85	141	142	129	115	24.8	16.4	7.7	7660		49.2	6.5	LANDING

DATA SHEET DEPT. FORM NO. 383-V-3

A/C T2C #1
PILOT WENZELL
NAV.

DATE 12-17-76
FLT. NO. 607

☒ FILM TYPE P.R.
☒ OSC NO 1

READ BY LH
WRITTEN BY
CALIB BY

TEST/MANEUVER LHS FLT #9

PAGE 1 OF 1

RUN	CORR	TIME	CLOCK	ALT	A/S	L/H RPM	CABIN FLOW	AFT COMP AIR				HEAT EX IN	HEAT EX OUT		OAT		P-P		OUT PORT	P-P			P-P	
			1	2	3	5	6	14-1	14-2	14-3	14-4	14-5	14-6		8	18			19			20		
				FT	KTS	RPM	GPM	°F	°F	°F	°F	°F	°F		°F	PSIG	PSIG		PSIG	PSIG		PSIG	PSIG	
1	378		1:15 6	27400	222.0	16390	.680	29	118	188	190	169	144		-14.9	15.1	2.2		8164	—		54.1	7.7	← RAW DATA ← REDUCED DATA
2	404		1:26 9	25180	265.0	14787	.655	-3	118	184	183	157	145		-11.5	19.5	2.2		8046			51.5	6.4	
3	427		1:34 31	30300	250.0	15710	.680	-5	120	187	186	163	146		-19.3	14.0	2.2		7967			52.8	6.4	
4	450		1:44 49	28245	283.0	15818	.690	-2	121	188	188	164	146		-3.7	15.1	2.2		7849			54.1	7.7	
5	481		1:55 12.5	24175	276.0	12257	.615	-5	113	178	174	153	138		+8.0	11.1	1.1		7690			45.2	6.4	
6	506		2:31 31	925	42	7801	.580	43	115	166	160	153	133		+15.8	18.4	14.2		7927			52.8	7.7	

DATA SHEET DEPT. FORM NO. 383-V-3

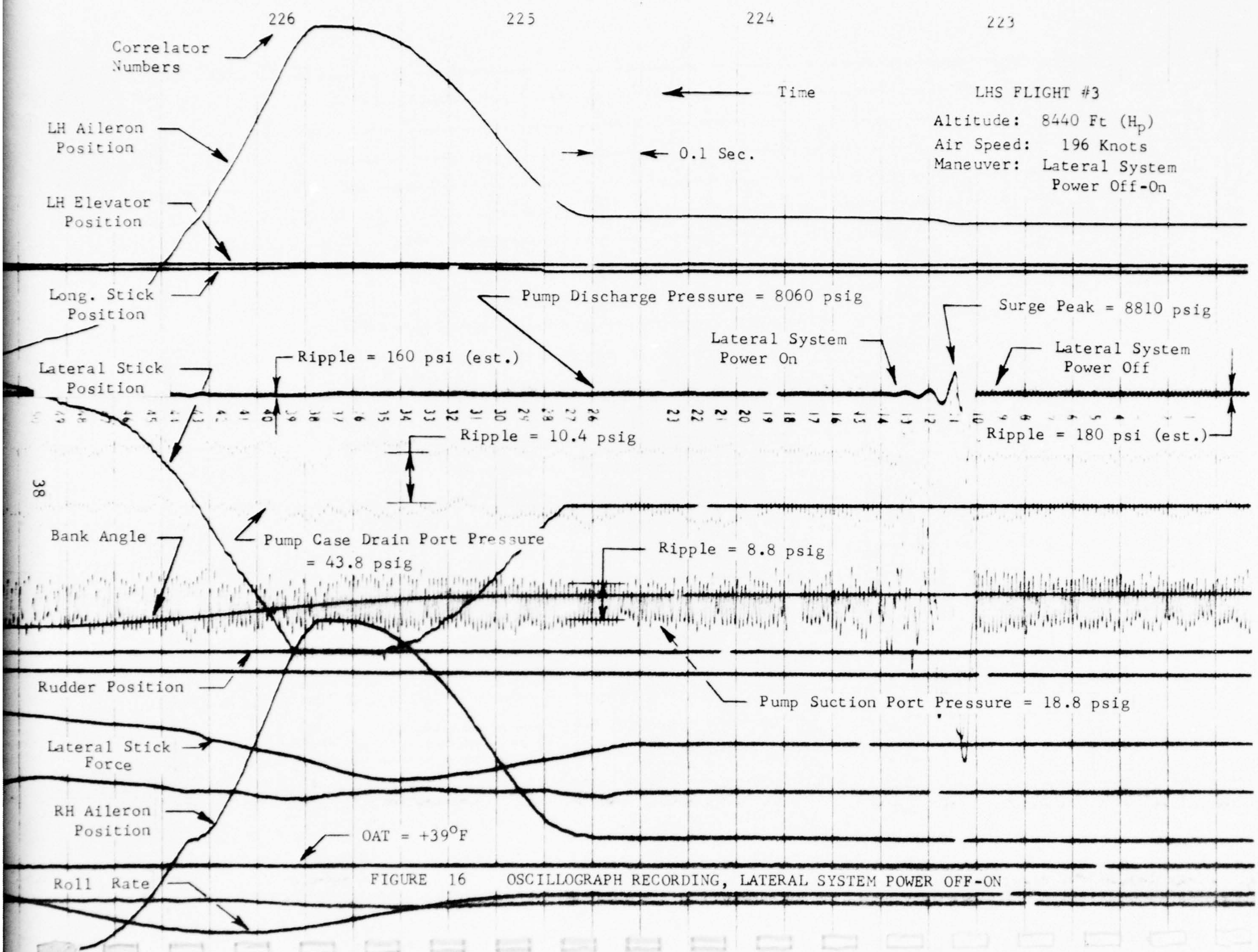


FIGURE 16 OSCILLOGRAPH RECORDING, LATERAL SYSTEM POWER OFF-ON

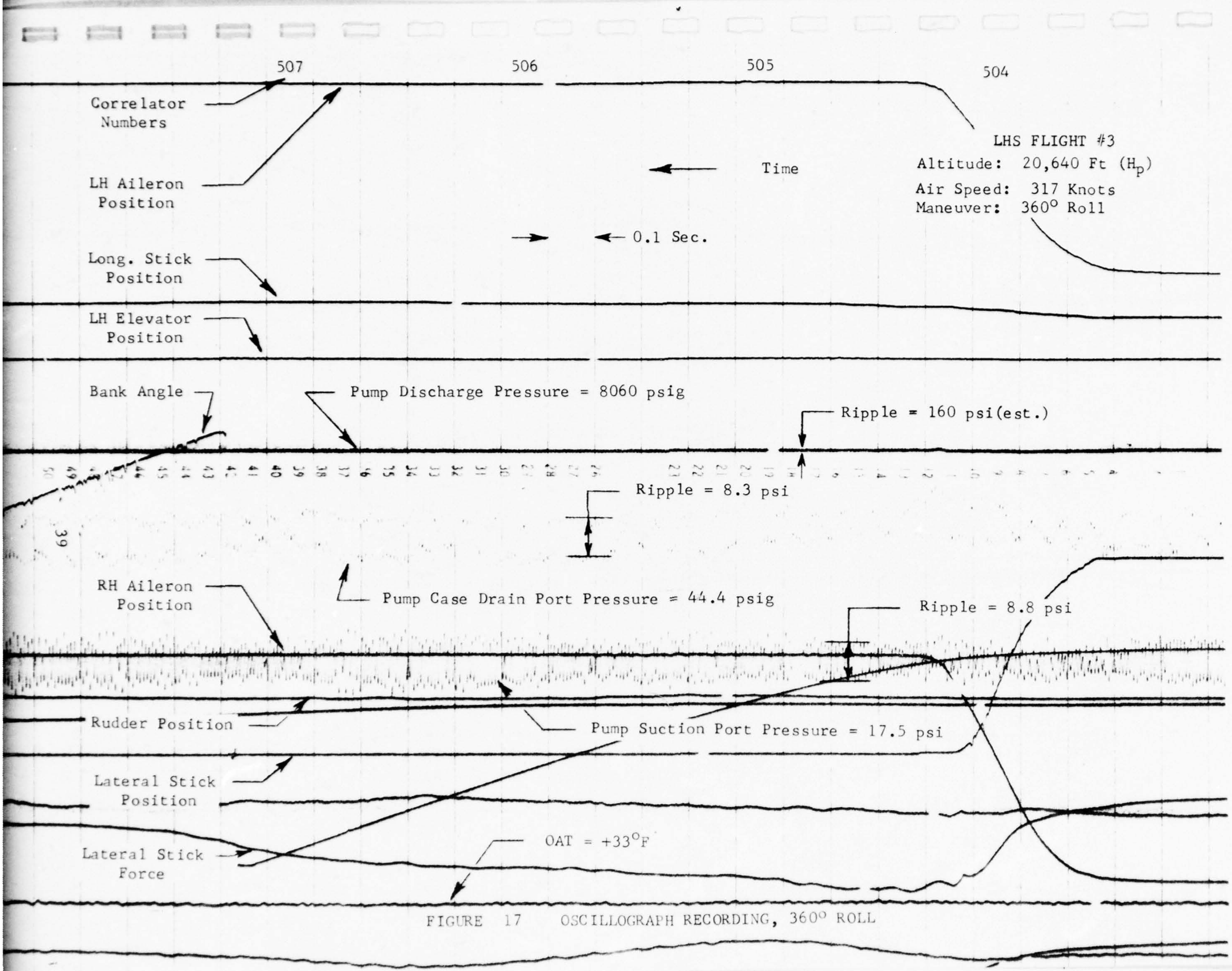


FIGURE 17 OSCILLOGRAPH RECORDING, 360° ROLL

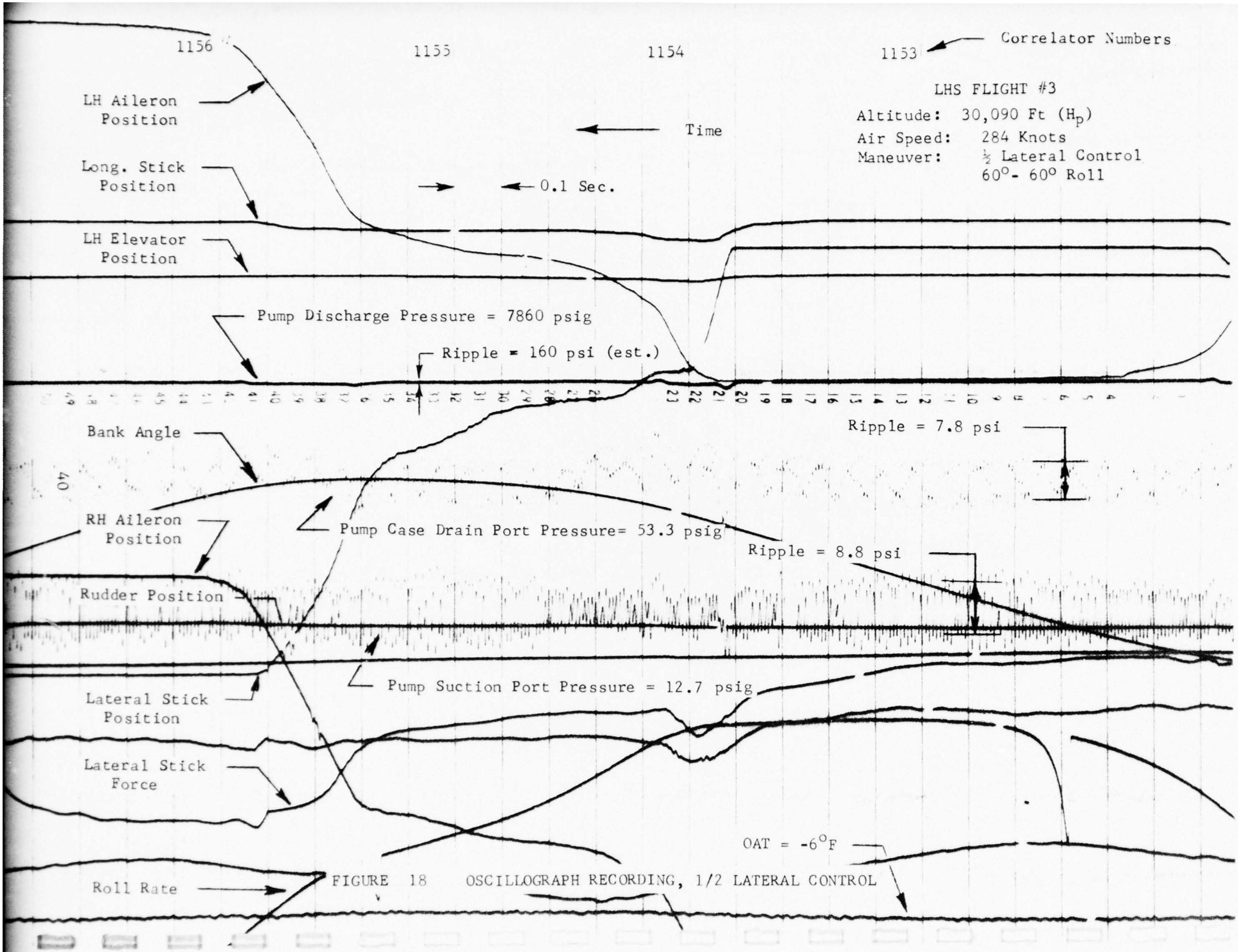


FIGURE 18 OSCILLOGRAPH RECORDING, 1/2 LATERAL CONTROL

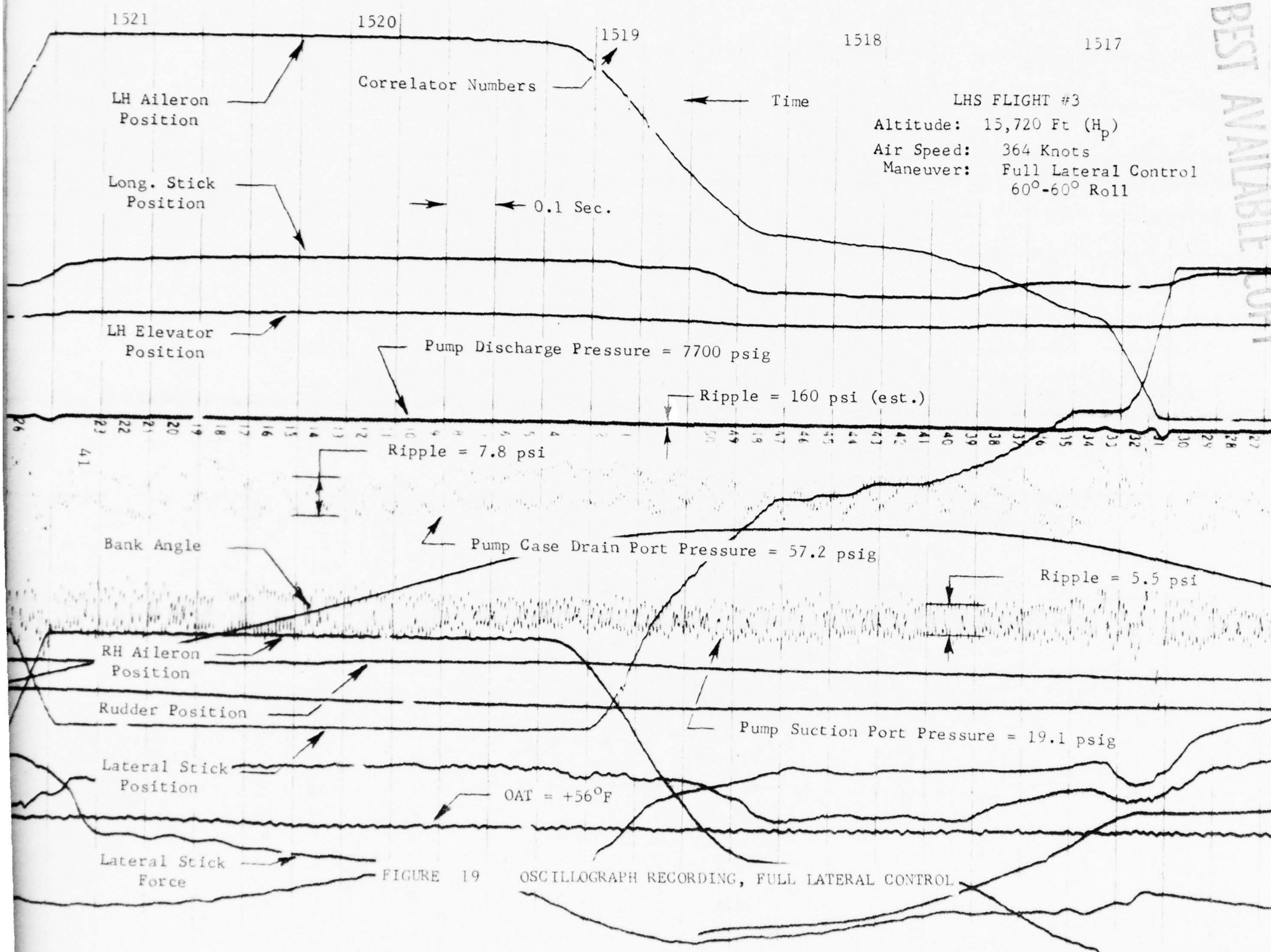


FIGURE 19 OSCILLOGRAPH RECORDING, FULL LATERAL CONTROL

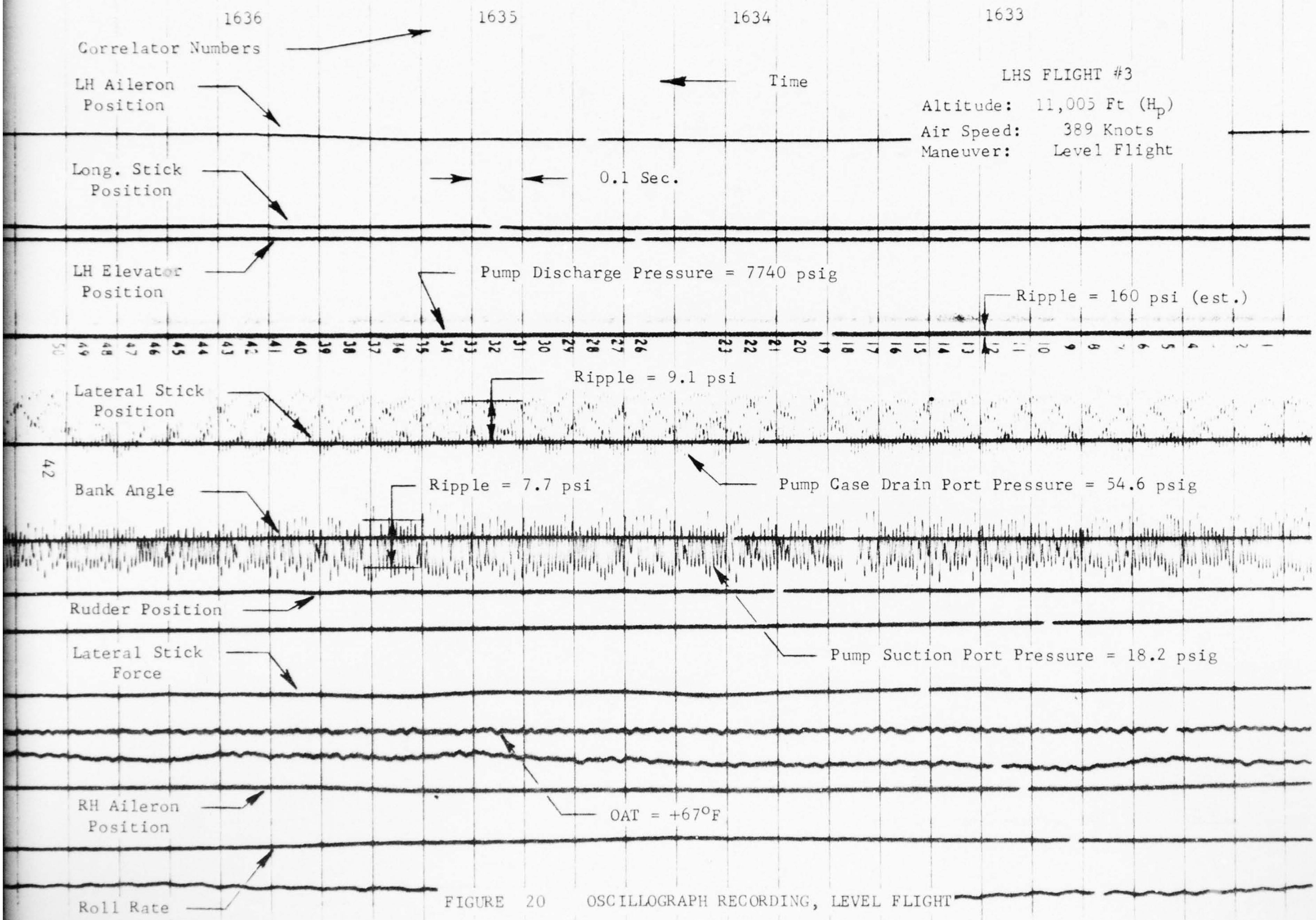


FIGURE 20 OSCILLOGRAPH RECORDING, LEVEL FLIGHT

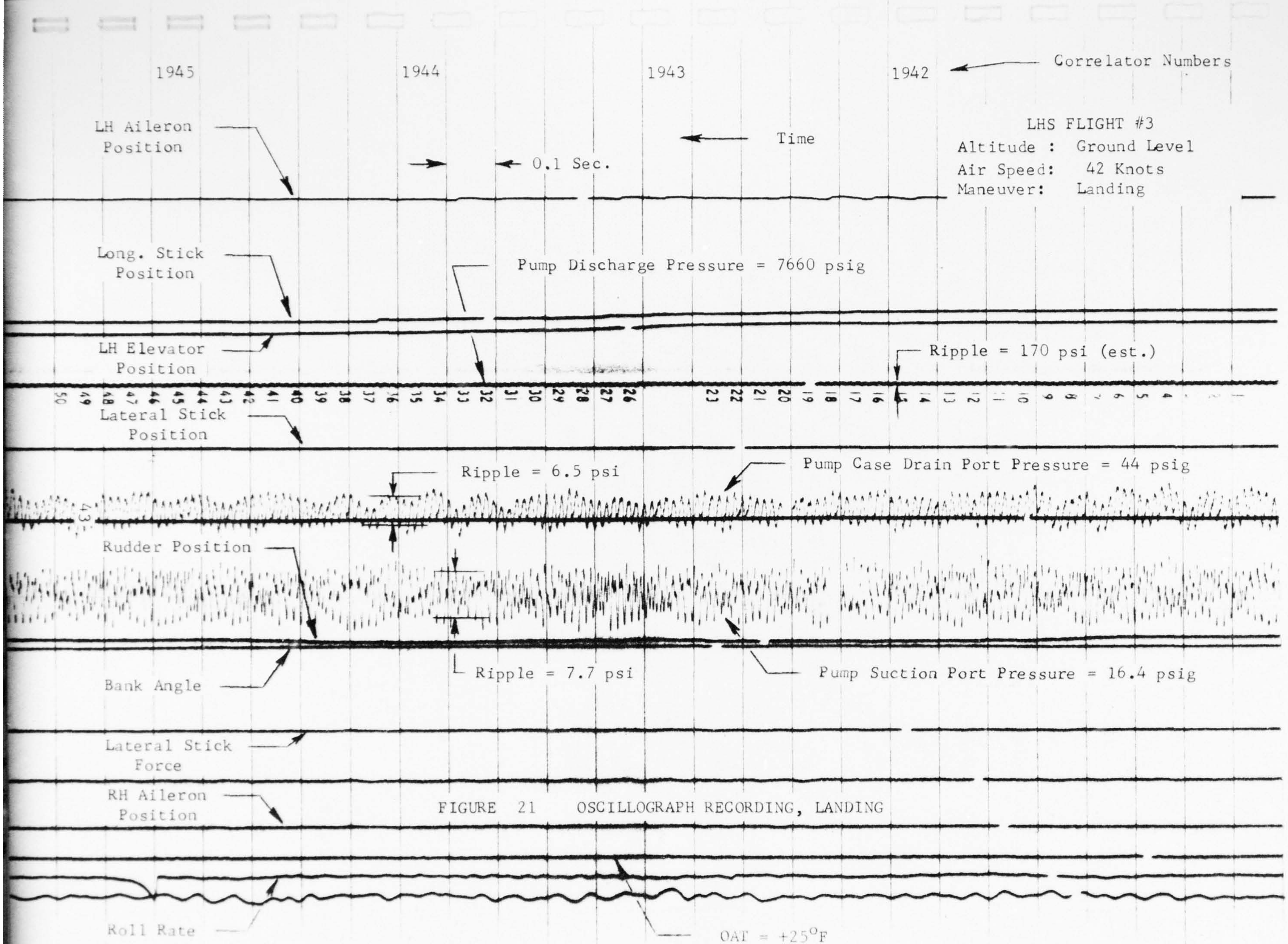


FIGURE 21 OSCILLOGRAPH RECORDING, LANDING

ROCKWELL INTERNATIONAL CORPORATION
COLUMBUS AIRCRAFT DIVISION
QUALITY ASSURANCE LABORATORIES

TEST REPORT

Date Rec'd in Lab NOTED

Article HYDRAULIC FLUID MIL-H-83282

Quantity 5

Source T-2C #1 8000 psi SYSTEM

Submitted By:

Specification NAVAIR 01-1A-17 Class 5

Name R. HANING

Test Required Contamination Analysis

Dept. 071 Ext. 2847

TEST DATA

Date	Source	Class	Results: Number of Particles per 100 ml — Range 5-10	10-25	25-50	50-100	+100	Comments
			Max No.					
		5	87000	21400	3130	430	41	
12-7-76	SAMPLE VALVE	3	23438	2486	106	12	0	AFTER 1 HR. RUN
12-9-76	" "	3	12005	1577	82	14	3	AFTER 1ST FLT.
12-14-76	* " "	2	4911	516	16	0	0	AFTER 3RD FLT.
12-15-76	" "	3	10610	1035	49	3	0	AFTER 5TH FLT.
12-16-76	" "	2	6216	1966	56	13	1	AFTER 7TH FLT.
12-20-76	" "	2	7121	1327	35	2	0	AFTER 9TH FLT.

* THIS SAMPLE TAKEN NEXT MORNING AFTER FLIGHT.
ALL OTHER SAMPLES TAKEN WITHIN ONE HOUR AFTER ENGINE SHUT-DOWN.

Disposition and/or Comments:

Signed W.E. Blackburn

Approved

Date 12-20-76

Distribution: B. HOLLAND

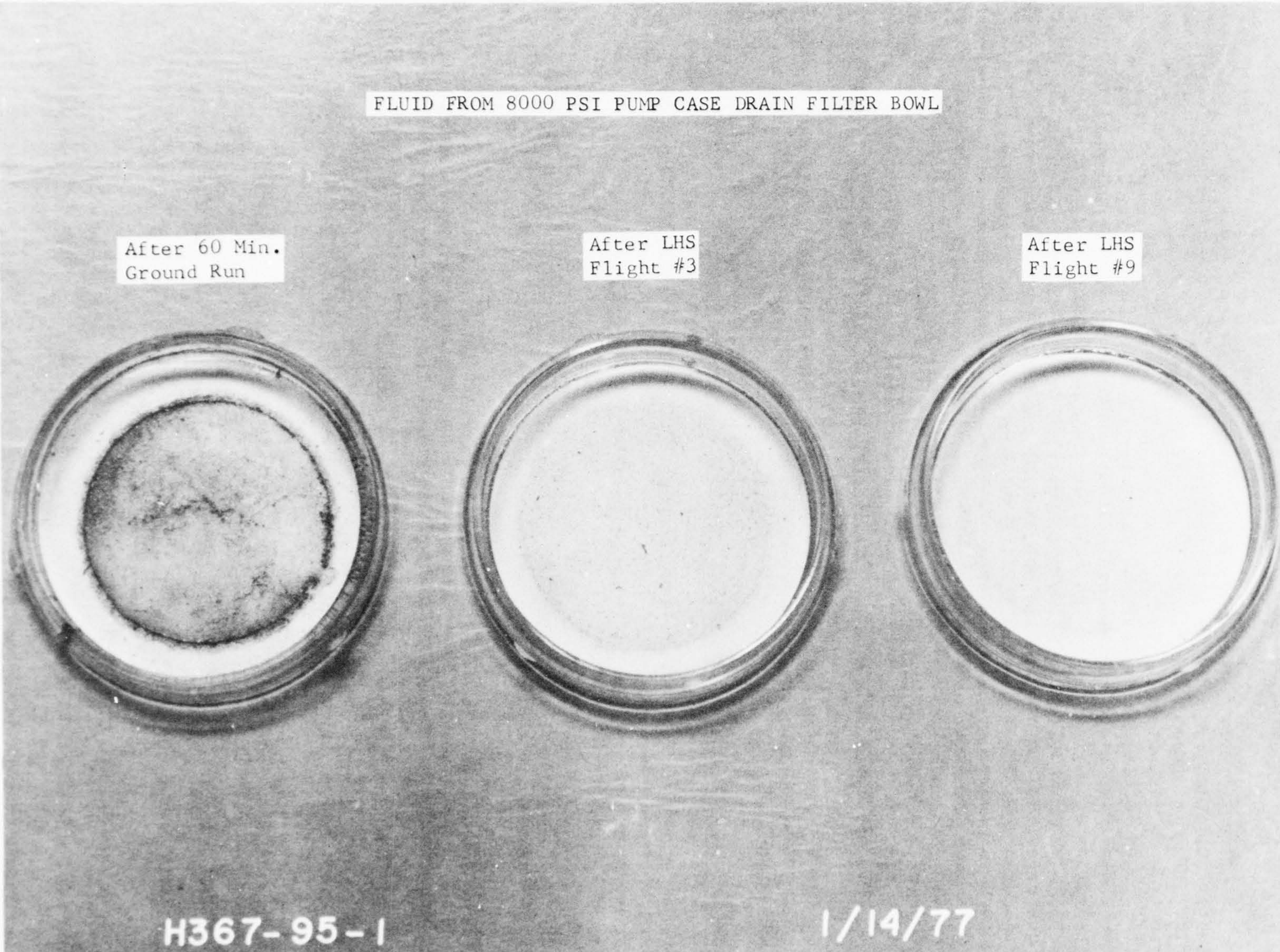


FIGURE 22 PATCH TESTS

6.0 DISCUSSION

A milestone has been achieved in the development of aircraft hydraulic systems -- an 8000 psi operating pressure was used for the first time to control the flight of an airplane. No problems whatsoever were encountered with the test installation. The system functioned exceptionally well and pilot response was favorable. Successful completion of this project corroborated prior analyses and laboratory investigations. The relative ease with which the flights were made confirmed that lightweight hydraulic systems can be designed, fabricated, and maintained without special techniques or state-of-the-art advances. These results fulfill the analyses and data requirements needed to progress from the current "exploratory phase" of the LHS program to the "advanced development phase." This new phase will bring the potential benefits of using 8000 psi hydraulic systems in military aircraft another step closer toward realization.

The following is a discussion covering important subjects relative to the use of 8000 psi hydraulic systems in military aircraft. The information presented was developed in the LHS program and is given here to disseminate current knowledge about various aspects of the LHS concept.

PUMP HEAT REJECTION AND ENDURANCE

Overall efficiency levels of conventional 3000 psi, variable delivery, aircraft-type pumps generally range from 85 to 92% at full flow, depending on operating conditions. The 8000 psi pumps developed for the LHS program have overall efficiency levels of 85 to 91%, References 5 and 8. When discharge flow is zero (at full cutoff), overall efficiency is zero. Pump heat rejection near full cutoff is a principal cause of fluid temperature rise in aircraft hydraulic systems.

Heat rejection rates of the 3000 psi and 8000 psi pumps used in the T-2C test installation may be compared. Both units were de-stroked versions of larger models. Basic information and flight test data are given below:

BASIC INFORMATION

PUMP M/N	RATED SPEED, RPM	DISCHARGE PRESS, PSIG	DISPLACEMENT, CIPR ACTUAL	DISPLACEMENT, CIPR MAX.	OUTPUT POWER, HP ACTUAL	OUTPUT POWER, HP MAX.
PV3-022-14 (Vickers)	7800	2850	.145	.220	8.14	12.35
AP1V-106 (Abex)	7800	7850	.100	.121	15.48	18.73

FLIGHT TEST DATA

(Flight 9, Run 3, Ref. p.37)

PUMP M/N	SPEED, RPM	PUMP CASE FLOW, GPM	FLUID TEMP., °F INLET	FLUID TEMP., °F CASE	HEAT REJECTION, BTU/Min.
PV3-022-14	7400	0.3(est)	+120	+186	70
AP1V-106	7400	0.68	+120	+187	168

If the 3000 psi pump had the same power output as the 8000 psi unit, heat rejection would increase to approximately 115 BTU/min. Heat rejection of the 8000 psi pump should be viewed from the standpoint of development; the LHS pump was the first of its type ever built. Minor design changes could be incorporated to lower heat rejection. For example, stroking piston leakage could be reduced without adversely affecting pump stability; a savings of approximately 40 BTU/min was estimated. This change alone would lower heat rejection to 128 BTU/min. Upgrading performance through such design improvements is a normal procedure in the development of any pump. Full development of LHS pumps should result in heat rejection rates comparable to those in similar sized 3000 psi units.

Military aircraft pumps are expected to have a life of 750 hours (MIL-P-19692B). The endurance capability of 8000 psi pumps must be comparable to 3000 psi units to be acceptable. Full scale endurance testing of an 8000 psi pump has not yet been accomplished, however, a significant number of hours have been accumulated during the course of LHS hardware development testing.

Two variable delivery models have been built by Abex Corporation for the LHS program:

Quantity	Model No.	Rated Performance
3	AP6V-57	14 gpm at 7850 psi & 4000 rpm
1	AP1V-106	3.4 gpm at 7850 psi & 7800 rpm

Both models were developed from existing hardware. No effort was made to minimize weight; cost was a primary concern. Total operating time (as of 1 January 1977) on the pumps is summarized below:

M/N	Total Accumulated Running Time, Hrs	Testing Conducted By
AP6V-57, #1	216	CAD
AP6V-57, #2	106	CAD
AP6V-57, #3	500 (Approx.)	NADC
AP1V-106	70	CAD

A total of approximately 900 hours have been accumulated on 8000 psi pumps thus far. No major problems have been encountered; the level of performance has been excellent, considering their stage of development. Pump endurance is not expected to produce any serious difficulties, since operating characteristics have been very similar to those of 3000 psi units.

CONTROL VALVE INTERNAL LEAKAGE CHARACTERISTICS

Three 8000 psi spool/sleeve type control valves have been built for the LHS program. Standard design procedures and conventional fabrication techniques were used in their manufacture. Spool/sleeve diametral clearances were in the range of 0.0002 to 0.0003 in. (total); this clearance is common in 3000 psi valves. Design features and power losses in two valves are given below:

	P/N 4212-03-11	P/N 4257-05
Spool diameter, in.	0.250	0.250
Spool travel (rated), in.	± 0.086	± 0.056
Design overlap, in.	± 0.0025	± 0.003
Flow control orifice type	Shovel notches	'V' notches
Rated flow, gpm	4.0	0.25
Null leakage, cc/min (+110°F inlet fluid, MIL-H-83282)	125	90
Null power loss, hp	0.15	.11

The power losses noted above compare favorably with losses in 3000 psi valves with similar horsepower ratings. The increase in fluid viscosity with pressure appears to have a beneficial effect on leakage through small clearances in 8000 psi units. Orifice erosion has been negligible. Performance of the LHS control valves has been completely satisfactory.

FLUID TEMPERATURE

Hydraulic systems generate heat because it is impossible to convert all input power into useful work. Thus, hydraulic systems normally operate at temperatures above ambient. Temperature stabilization is reached when the heat loss rate equals the generation rate(input power minus output work). Fluid temperatures must be maintained within the fluid temperature envelope to prevent thermal breakdown of the fluid and seals. For Type II systems the maximum temperature is +275°F (MIL-H-5440); for Type III systems it is +390°F (MIL-H-8891). If heat dissipation through conduction, radiation, and convection is not sufficient to maintain reasonable fluid temperatures, then a heat exchanger is required. A hydraulic system must be designed so that a heat balance is achieved at a satisfactory operating temperature.

The principal sources of heat generation in hydraulic systems are:

1. Pump and valve internal leakage
2. Orifices and valves used to throttle and control flow (These devices are inherent heat generators)
3. Resistive pressure drops in lines, fittings, and porting passageways

The principal means of heat dissipation are:

1. Conduction from hydraulic system components through attachments into aircraft structure
2. Convection aided by air flow around surface areas of system components
3. Radiation from system components

Since operating temperatures are related directly to the ability of the system to dissipate heat, cooling requirements will be somewhat greater due to the inherent compactness and reduction in exposed area of 8000 psi systems (assuming 3000 psi and 8000 psi pump efficiencies are the same). Smaller fluid volume in 8000 psi systems will also contribute toward higher temperatures. Therefore, 8000 psi systems must be carefully designed so that maximum fluid temperatures are within the fluid temperature envelope.

ACTUATOR DYNAMIC SEAL LIFE

Four (4) 8000 psi servo actuators have been designed and built by CAD, Table IV. Two of the units, P/N 4212 and P/N 4257, were for the LHS program. P/N 4248 and P/N 4262 were for the Advanced Flight Control Actuation System (AFCAS) program, References 9 through 12.

Each actuator has a three piece, split ring, metallic piston seal. The rod seals are two-stage. The first stage (high pressure) is a five-piece metallic seal in P/N's 4212, 4248, and 4257, and elastomeric in P/N 4262. The second stage is a standard O-ring/backup ring configuration. The two-stage design minimizes seal wear because the first stage is well lubricated and the second stage operates at return pressure.

A 100 hour endurance test was conducted on the seals at 8000 psi and +200°F, Reference 7. A total of 440,000 piston oscillations were completed; seal performance was satisfactory. An additional 100 hours of testing is scheduled for the near future. The endurance capability of the metallic piston seal was judged to be very good. Life expectancy of the two-stage rod seal is anticipated to be satisfactory, however additional testing is required to determine its potential.

TABLE IV

8000 PSI ACTUATORS DESIGNED AND BUILT AT CAD

CAD P/N	TYPE	INPUT	MID-STROKE LENGTH, IN	PISTON STROKE, IN	MAX. OUTPUT FORCE
4212	For lab tests, dual system tandem, balanced piston	Manual	46.2	8.2	26,000 lb/chamber
4248	For lab tests, dual system tandem, partially balanced, modular construction	Electrical (torque motor driven valve)	38.3	8.2	46,000 lb extend 36,000 lb retract
4257	For T-2C aileron, single system, balanced piston	Manual	15.2	3.0	1870 lb
4262	For T-2C rudder, single system, balanced piston, modular construction	Electrical (torque motor driven valve)	16.6	3.5	1870 lb

ACTUATOR STIFFNESS

Weight savings produced by operating at 8000 psi instead of 3000 psi begins with smaller net areas on actuator pistons. Lower flow demand because of less displaced fluid results in a general decrease in the size of supply lines, pumps, reservoirs, etc. Use of a smaller piston area, however, reduces actuator physical stiffness which in turn lowers system resonant frequency. Mechanical elements which contribute to physical stiffness include bearings, piston/rod, cylinder, and actuator end pieces; hydraulic elements are the fluid and seals. Based on practical experience, it has been found that actuator physical stiffness is approximately equal to the stiffness of the fluid column. Thus,

$$K_f = \frac{4\beta_f A \eta}{S}$$

Where, K_f = Stiffness due to fluid compressibility (actuator piston at mid-stroke)

β_f = Bulk modulus of fluid (taken at one-half system pressure (approximately 15% higher at 4000 psi than at 1500 psi)

A = Piston net area

S = Piston Stroke (total)

η = Ratio of fluid volume swept by the piston to the total fluid volume contained between the piston and control valve, typically between 0.85 and 0.95 for an integrally mounted valve.

In a practical hardware installation, the actuator backup structure, the actuator, and the control surface are three significant springs. Control surface inertia is the only significant mass. The three springs are in series, anchored to the aircraft at one end and supporting the mass at the other. If the spring rates of each are assumed equal, then the actuator is twice as stiff as the combined structure/surface spring. Normally, however, the actuator is the stiffest spring in the system.

Physical stiffness is the composite effect of mechanical and hydraulic compliant elements between the actuator mounting points. Actuator effective stiffness is due to closed loop servo action, and is related to loop gains and control valve performance characteristics.

$$K_s \approx K_p A$$

where, K_s = effective static stiffness (at ω = 0)

K_p = control valve pressure gain
(this value is approximately 8/3 higher in 8000 psi valves than in 3000 psi valves)

A = Actuator piston net area

Frequency response tests of similar sized "muscle" actuators operating at different pressure levels were conducted in a rigid mass load fixture, Reference 3. Damped natural frequencies observed were:

Actuator	Operating Pressure	Resonant Freq.
CAD P/N 247-58716	3000 psi	27 Hz
CAD P/N 4212-01	6000 psi	24 Hz
CAD P/N 4212-01	9000 psi	22 Hz

Performance characteristics of the 6000 and 9000 psi actuators were very similar to the 3000 psi actuator for large amplitude, manual-type inputs. For small amplitude inputs, such as those encountered with automatic control, response capabilities of the 6000 and 9000 psi actuators were satisfactory to 10 Hz. The reduction in resonant frequency noted above was not considered critical.

Although actuator physical stiffness is fundamentally reduced by going to higher operating pressures, this is partially offset by an increase in fluid bulk modulus. The net change should not degrade system performance significantly in conventional applications because of lesser stiffness in mounting structures. Furthermore, control techniques and devices are available to offset effects caused by reduced physical stiffness.

PRESSURE SURGES

Pressure surges are normal in aircraft hydraulic systems and are an important design parameter because of their affect on the fatigue and functional characteristics of system components. Surges result primarily from:

(1) Sudden stopping of high velocity fluid

(2) Sudden porting of high pressure fluid into a chamber filled with low pressure fluid

(3) Bottoming of an actuator piston

(4) External energy derived from load inertia

When the flow of a mass of fluid is suddenly decelerated by a rapidly closing valve, waterhammer results; this is usually the most severe pressure transient encountered in hydraulic circuits. Assuming instantaneous valve closure, this surge may be calculated by

$$\Delta P = V\sqrt{\rho \beta_e}$$

Where, ΔP = Maximum pressure rise above system pressure

V = Fluid velocity

ρ = Fluid mass density

β_e = Effective bulk modulus (fluid compressibility + tube elasticity)

Pump response time is also a factor causing surges. Operation of the delivery control mechanism normally occurs in 0.050 sec. or less. Thus, when a valve closes, the pump momentarily continues to discharge fluid until the control mechanism adjusts to the new flow demand; this can result in a pressure overshoot.

Surges in 8000 psi systems are less, percentage-wise, than in 3000 psi systems because of:

- Better damping at 8000 psi due to increased fluid viscosity

- The minor effect of operating pressure level on waterhammer magnitude (ρ and β_e)

Typical peak surges observed in a laboratory system designed and operated to compare surges at 3000 and 8000 psi are listed below: (References 4 and 5)

System	Peak Pressure	Overshoot
3000 psi	3900 psi	130%
8000 psi	9200 psi	115%

The maximum allowable surge in 3000 psi systems is 135%, reference MIL-H-5440. The maximum allowable surge in 8000 psi systems was established at 120% in Reference 4. The validity of the 120% design value has been confirmed by both laboratory and flight testing.

Pump discharge pressure ripple is a function not only of pump design, but also of pump/system interaction characteristics. Ripple has generally been less than 200 psi peak-to-peak or 2.5% in 8000 psi systems, Reference 5. Ten percent ripple is allowed at 3000 psi (MIL-P-19692B).

HYDRAULIC FLUID SELECTION

Lightweight hydraulic system development testing was conducted initially (in 1968) using MIL-H-5606, Reference 2. This fluid exhibited poor shear stability due to polymeric additives employed to improve its viscosity-temperature coefficient. MIL-H-27601 was used for tests reported in References 3 and 4 because of its excellent shear stability. MIL-H-27601, however, is a high temperature hydraulic fluid and very viscous at low temperatures. MIL-H-83282 was subsequently evaluated as a possible candidate for 8000 psi systems, References 5, 13 and 14. This fluid is rated for use at temperatures from -50 to +400°F, is shear stable, and less flammable than MIL-H-5606. Physical properties of MIL-H-83282 are given in Reference 15.

Shear stability is particularly important in a fluid required to operate at high pressure levels. A non-Newtonian fluid, such as MIL-H-5606, can experience either temporary or permanent viscosity losses when it is subjected to high shear rates. Temporary losses occur during laminar flow. Permanent losses can result from severe turbulence, cavitation, and large pressure drops across sharp edged orifices. These conditions can stress molecular chains to the breaking point resulting in a less viscous fluid. At high operating temperatures, reduced viscosity causes increased power losses due to higher internal leakage rates, and increased wear due to less lubricity.

MIL-H-83282 is a synthetic hydrocarbon and has exhibited excellent shear stability and lubricity characteristics in tests conducted at 8000 psi by CAD and the Naval Air Development Center. It is anticipated that further testing should establish MIL-H-83282 as a satisfactory fluid for lightweight hydraulic systems.

TUBING PRESSURE LOSSES

Fluid flow is usually turbulent in aircraft hydraulic systems. Under turbulent flow conditions, line losses at 8000 psi are identical to those at 3000 psi (for the same flow rate, and tube I.D. but with 2.67 times more horsepower transmitted), Reference 4. Since 8/3 more pressure is available at 8000 psi than at 3000 psi, 8/3 higher line losses are permissible in 8000 psi systems without sacrificing performance. Therefore, under normal operating conditions, line losses at 8000 psi are less percentage-wise than at 3000 psi. Typical pressure drops in tubing at 3000 psi and 8000 psi are compared below, based on a given horsepower level, 15 ft/sec fluid velocity at 3000 psi, and using MIL-H-83282 fluid.

Operating Pressure, psi	Tube Size	Fluid Velocity, ft/sec	Horsepower Transmitted	% Loss of Sys.Press. per Foot of Tubing		
				0°F	+100°F	+200°F
3000	3/8 x .022	15	7.05	1.33	.059	.050
8000	1/4 x .025	15.4	7.05	2.41	.098	.041
3000	1/2 x .029	15	12.57	.75	.034	.035
8000	3/8 x .038	12	12.57	.86	.035	.017

At low operating temperatures, the fluid in 8000 psi lines will heat up faster than in 3000 psi lines because of the higher allowable pressure drop. This effect will reduce fluid viscosity, decrease losses, and shorten warm-up time in 8000 psi systems.

APPLICATION OF THE LHS CONCEPT

Primary factors affecting applicability are hydraulic system size and power requirements of the aircraft. In complex systems with large lines and long runs, significant reductions in tubing weight and fluid weight can be realized by operating at 8000 psi. In smaller systems using smaller lines, size reductions are limited by manufacturing and handling considerations such as minimum practical tubing diameter and wall thickness rather than flow velocity and pressure drop. Actuators in large systems are generally big enough to permit a reduction in size if operated at 8000 psi, resulting in significant volume savings. Actuators in smaller systems have relatively low force outputs and consequently little potential for volume reduction. The potential for weight savings in pumps and reservoirs depends primarily on the degree of success in decreasing the volume of actuators and lines.

It can be concluded that if reductions in line diameters or actuator sizes are restricted, weight savings achieved applying LHS technology will be limited. As a rule-of-thumb, if a hydraulic system uses more than 100 hp, the full potential of the LHS concept can be realized -- 30% weight savings and 40% space reduction. In smaller systems, weight and space savings will be less.

The space savings advantage provides a further benefit in the area of vulnerability. The smaller size tubing, actuators, reservoirs, etc. used in 8000 psi systems have less projected area, making them less vulnerable to hostile ground fire.

A study was conducted to assess the benefits of applying LHS technology to helicopter hydraulic systems, References 16 and 17; among the parameters evaluated was vulnerability. Using the equivalent singly vulnerable area approach, the 8000 psi system was determined to be 48% less vulnerable than the baseline (CH-47C) 3000 psi system.

BASELINE CRITERIA

Data presented in this report have been evaluated and judged to be satisfactory on the basis of criteria developed in Reference 4, engineering assessments, and pilot comments. An additional basis for evaluation is available -- results of flight demonstration testing. Demonstration tests on the 3000 psi hydraulic system in the T-2 airplane were conducted in accordance with MIL-T-5522 and reported in NA59H-544. CAD report NA59H-544 was examined to determine if any performance discrepancies occurred in the 8000 psi test installation, based on a comparison with 3000 psi system performance data. All of the data and pilot appraisals on the 8000 psi system were considered compatible with the 3000 psi demonstration test results.

7.0 RECOMMENDATIONS

EXPLORATORY PHASE

Work is nearing completion on the exploratory phase of the LHS development program; analyses, laboratory investigations, and flight testing have all been accomplished successfully. Endurance capabilities of 8000 psi components, such as the pump, fluid, seals, etc., have been determined on a limited basis, Reference 7. Additional testing would provide important data on the potential life of these components. It is therefore recommended that the system used for the 100 hour endurance test reported in Reference 7 be subjected to 100 additional hours of endurance cycling at 8000 psi and +200°F.

ADVANCED DEVELOPMENT PHASE

Development of a new concept normally begins with small scale exploratory investigations in which analyses and laboratory testing are conducted on high risk areas. When the results have produced a sufficient level of confidence, the program then proceeds into a larger scale, advanced development phase. Results of LHS flight testing were excellent and significantly increased confidence in using an 8000 psi operating pressure in aircraft. All essential investigations have thus been accomplished in the exploratory phase. Rockwell International therefore recommends that the LHS program progress into the advanced development phase, Appendix B.

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LIST OF ABBREVIATIONS

AFCAS	Advanced Flight Control Actuation System
A/S	air speed
alt.	altitude
approx.	approximately
BTU/min	British Thermal Units per minute
CAD	Columbus Aircraft Division
cc	cubic centimeters
cc/min	cubic centimeters per minute
CIPR	cubic inches per revolution
CORR	correlator
CRES	corrosion resistant
EGT	exhaust gas temperature
°F	degrees Fahrenheit
FRP	flight reference plane
F.S.	fuselage station
ft.	feet
ft/sec	feet per second
GCA	ground control approach
GFE	government furnished equipment
gpm	gallons per minute
hp	horsepower
H_p	pressure altitude (29.91 in. Hg = Sea Level)
Hz	Hertz (cycles per second)

I.D.	inside diameter
in.	inch
in^2	square inches
lb	pound
KOAS	knots observed air speed (uncorrected)
LH, L/H	left hand
LHS	Lightweight Hydraulic System
L/R	left and right
MAC	mean aerodynamic chord
max.	maximum
M/N	model number
Min.	minute (time)
MRP	military rated power
MRT	military rated thrust
MN	mach number
NADC	Naval Air Development Center
No.	number
OAT	outside air temperature
O.D.	outside diameter
P-P	peak-to-peak
ΔP	differential pressure
PA	power approach (landing configuration)
PCL	power control lever
PLF	power for level flight
psi	pounds per square inch
psia	pounds per square inch absolute pressure

psig	pounds per square inch gauge pressure
P/N	part number
RH, R/H	right hand
rpm	revolutions per minute
sec	second (time)
S&L	straight and level
T/O	take-off
vdc	volts direct current
V_h	maximum velocity for level flight
V/STOL	Vertical/Short Take-Off and Landing
$\approx$	approximately equal to
#	pounds

APPENDIX A

TEST PROCEDURES

This section details procedures used for ground checking and flight testing the 8000 psi lateral control test installation.

A.1 FLUSHING AND FILLING PROCEDURE

The purpose of the following procedure is to remove as much MIL-H-5606 fluid (red) as practical, replacing it with MIL-H-83282 fluid (amber). A 3000 psi ground cart containing MIL-H-83282 fluid is required.

Prior to flushing and filling, notify B. Holland (X2713) or B. Haning (X2847) to verify plumbing hookup.

Fill and Suction Lines

- Open reservoir drain line.
- Attach 3000 psi ground cart to fill fitting on A/C. Fill at approx. 1.0 gpm and 85 psi max. Continue to fill until fluid runs reasonably clear (amber).

  NOTE: Compare with fluid in cart to make judgment.
- Cap reservoir drain line.
- Remove RH pump suction hose (at pump end) and add fluid through the fill line until fluid draining from hose runs reasonably clear.
- Reinstall RH pump hose and repeat for LH pump.
- Reinstall LH pump hose.

8000 psi Pressure Line

- Open reservoir drain line.
- Remove LH pressure hose at pump end and attach 3000 psi ground cart pressure line to fitting (dynatube adapter required).
- Disconnect aileron actuator pressure hose at actuator end, attach adapter, and drain hose to collect fluid.
- Flush at approximately 1.0 gpm (at less than 500 psi) for one minute (aileron power switch "ON").
- Reconnect aileron actuator hose. Gradually increase pressure to 1000 psi and cycle aileron actuator at least 10 times.
- Remove ground cart pressure line and reinstall pump hose.

3000 psi Lines

- Maintain reservoir drain line open.
- Drain and fill cart fill line (hose).
- Attach 3000 psi ground cart pressure hose to external A/C disconnect.
- Gradually increase pressure to 3000 psi and cycle each subsystem in the following order:

	COMPLETE CYCLES
LATERAL MASTER (VARIABLE STAB. SYS)	4
ARRESTING HOOK	2
SPEED BRAKES	3
LANDING GEAR	2
ELEVATOR ACTUATOR	4

- If fluid draining from reservoir is not reasonably clear, repeat cycling procedure.
- Drain and fill cart fill line (hose).
- Close reservoir drain and fill reservoir through aircraft fill connection.

Air Removal

- Attach 3000 psi ground cart pressure, fill, and suction lines to the aircraft.
- Apply 85 psi at fill fitting and bleed air from heat exchanger at bleed port located at the upper, left aft corner of the heat exchanger.
- Bleed other portions of system as required.

A.2 HANGAR TESTS

Hydraulic Fluid Contamination

- Take fluid sample for particulate count. Open sampling valve upstream of reservoir return filter. Operate elevator slowly. Discard first 1/2 pint of fluid before taking sample. Close valve.

- Remove pump case drain filter bowl. Take bowl, filter, and fluid to lab for patch test.

Fluid Leak Check (8000 psi system)

Connect 10,000 psi power supply - Remove hose at pump pressure port and connect to discharge hose of 10,000 psi power supply. Connect hose from 10,000 psi power supply reservoir to the Tee immediately upstream of the filter at the T-2C hydraulic reservoir return port. Plug motor cord into a 440 volt, 30 amp receptacle. Check direction of rotation of motor.

Leak Check Procedure

- With aileron power "on", turn on 10,000 psi power supply and adjust relief valve to 3000 psi. Make visual check for leaks at all newly installed pressure lines. Operate aileron actuator, look for leaks.

- Repeat with 8000 psi applied.

- Repeat with pressure sufficient to crack relief valve (8800 to 9000 psi).

Lateral System Operation Check

An operator familiar with the "feel" of the T-2C 3000 psi lateral system shall conduct this check.

- With 8000 psi applied, lateral power "Off", operate ailerons. Note "feel" and make comments.

- Repeat with aileron power "On".

- Reconnect A/C hose to pump pressure port. Disconnect return line hose. Cap fitting at Tee.

3000 psi System Checkout

Connect 3000 psi ground cart to aircraft. Operate the following: elevators, main gear, speed brakes, and lateral master actuator. Check for leaks and normal operation.

Heat Exchanger Check

- Apply 28 vdc external power to aircraft. Turn on No. 2 inverter; the heat exchanger blower should now be operating.
- Check for direction of air flow, vibration, major air leaks, and motor temperature rise after 15 minutes running time.
- Measure compartment air static pressure with the heat exchanger motor operating and all access doors closed (D/71).
- Measure suction pressure in inlet line near scarfed opening.

Preparation for Ramp Tests

- Attach 3000 psi ground cart to fill fitting. Apply 85 psi.
- To ensure the LH pump suction line is full, loosen the line fitting at the suction port and bleed fluid. Retighten fitting.
- To ensure the LH pump case is full of fluid, remove line at pump case drain port and cap line. Wait for fluid to come from case drain port. Reconnect case drain line.
- Service reservoir in accordance with Spec. HA0201-259, paragraph 4.2.7.

A.3 RAMP TESTS

Hydraulic System Resonance Search

- Open LH engine front access door and RH hydraulic bay access door.
- Turn aileron power "On".
- Start both engines and run at 75% rpm for 10 minutes to heat up hydraulic fluid. Shut down.
- Turn on oscillograph and photo recorder. Use 4 in/sec film speed and 2 frames/sec.
- Dept. 071 personnel will observe pressure galvos in oscillograph during this test.
- Start No. 1 engine. Slowly increase speed from 48% (idle) to 100%. Take approximately 2 minutes. Slowly decrease engine speed from 100% to 48% (take approx. 2 minutes). Shut down.
- After engine stops rotating, turn off oscillograph and photo recorder.
- Repeat with aileron power "Off".
- During engine runs (above) visually observe 8000 psi pressure lines for vibration and look for leaks.

Pressure Surge Investigation

- Start No. 1 engine. Increase engine speed to 94% (cruise) and hold.
- Turn on oscillograph and photo recorder.
- Turn aileron power "On" and "Off" 3 times (approx. 2 sec. between switching). Turn power "On".
- Operate aileron actuator with hardover inputs, from full up to full down, 3 times.
- Turn off oscillograph and photo recorder.
- Shut down engine.
- Process film and examine pressure data for hydraulic resonance.
- If no serious hydraulic resonance is found, proceed with ramp test. If serious hydraulic resonance is found, it must be corrected before testing can proceed.

System Operation, Heat Rejection Test, and Instrumentation Checkout

- Clean pump case drain filter bowl.
- Change system pressure and return filter elements.

The following test will simulate a one hour flight from takeoff to landing. Recorders will be operated the same as during an actual flight. Observe "oil hot" warning light for possible early shutdown, if required.

NOTE: 1. A "data burst" (DB) as used below is defined as turning the oscillograph and photo recorder "ON" for approximately 15 sec., then turning them "OFF".

2. Run both No. 1 and No. 2 engines

SIMULATION	ENGINE SPEED, %	ELAPSED TIME, MIN	OSCILLOGRAPH & PHOTO RECORDER	AILERON & ELEVATOR OPERATION
Aileron Power "On"				
Engine Start	0 to 48%	0→1/4	On	No
System Checkout & Taxi Out	48%	1	DB	Periodic
		9	DB	
Take-Off	100%	10	DB	Periodic
		14	DB	
Cruise	90%	15		Periodic
		25	DB	
	100%	26		
		28	DB	
	90%	29		
		34	DB	
	100%	35		
		37	DB	
	90%	38		
		43	DB	
	80%	44		
		50	DB	
Landing and Taxi-In	48%	51		Periodic (+ Speed Brakes)
		59	DB	
Engine Shutdown	48% to 0	60	On	
Temperature Soak-Out	0	61	DB	No
		70	DB	
		80	DB	

- During the simulated flight, measure two air temperatures in the aft fuselage bay -- one near the forward bulkhead, one near the aft bulkhead.

- Process film and reduce test data.

Preparations for Flight Testing (In Hangar)

- Hook up 3000 psi ground cart pressure and suction lines, apply 500 psi.

- Take fluid sample (within one hour after ramp test) for particulate count. Open sampling valve upstream of reservoir return filter. Operate elevator slowly. Discard first 1/2 pint of fluid before taking sample. Close valve.

- Remove pump case drain filter bowl. Take bowl, filter, and fluid to lab for patch test.

- Wipe off all access door inside surfaces near hydraulic lines to aid in determining where future leaks occur.

- Mark position of fluid level on reservoir sight glass.

Flight Clearance

- Review LHS program and T-2C 8000 psi system details with government flight representative.

- Obtain clearance for flight

A.4 PILOT INFORMATION

The modified system operates at two pressure levels concurrently: 3000 psi and 8000 psi. An 8000 psi pump mounted on the LH engine supplies power to an 8000 psi aileron surface actuator; a 3000 psi pump on the RH engine powers all remaining T-2C hydraulic subsystems. The 3000 and 8000 psi systems utilize a common reservoir and common return lines.

The modified system operates functionally the same as the original 3000 psi system, except as follows:

1. Aileron power shutoff is provided by an 8000 psi solenoid valve which is controlled by a switch located on the pilot's auxiliary instrumentation control panel.

   NOTE: For total power shutoff, both the above switch and the normal hydraulic power switch must be moved to "off".

2. The 3000 psi #1 pump output gauge is deactivated. Output from the 8000 psi pump is displayed on the upper right hand side of the pilot's instrument panel.

   NOTE: The pressure displayed is downstream of the aileron actuator shutoff valve and will fall to zero when the aileron power switch is at "off".

3. An "oil hot" light has been provided on the pilot's auxiliary instrumentation panel. This light indicates excessive hydraulic system oil temperature. Actuation of the light is an indication of system malfunction.

4. The 3000 psi system flow capability is reduced to one-half that of the conventional T-2C aircraft, since it contains only one pump. Actuation of high flow subsystems (speedbrakes and landing gear) at less than 100% engine RPM may result in slower than normal actuation rates, momentary drops in system pressure, or flickering of the power-off caution light. These occurrences should be considered normal for this system configuration.

5. A flight ceiling of 20,000 feet is recommended, however, higher altitudes can be flown if care is exercised to avoid large flow demands when engine speed is low. Under these conditions, suction line pressurization will be marginal at the 3000 psi pump and pump prime may be lost. Operation at 15,000 feet (approx.) should restore pump prime, however.

6. Contingency recommendations:

- If the "oil hot" light comes on, terminate flight. Reduce the power setting and alternately cycle the speedbrakes and landing gear during the return flight to lower bulk fluid temperature. Stop cycling when fluid temperatures become normal.

- If the left and right roll responses become significantly different for equal inputs, a malfunction in the aileron actuator is indicated. Terminate flight. Turn the aileron power switch "off". If possible, turn off the No. 1 engine for the return flight.

- If the 8000 psi system pressure drops below 6000 psi, terminate flight. Turn the aileron power switch "off". If possible, turn off the No. 1 engine for the return flight.

- If an emergency requires shutdown of the No. 1 engine, normal windmilling should provide sufficient pressure to operate the aileron actuator.

A.5 FLIGHT PLAN

1st Flight: Max. Altitude 20,000 ft.
Max. Speed 250 KOAS

Perform the following maneuvers at 10,000 and 15,000 ft.:

- Lateral control power "off" check @ 200 KOAS, PLF
- Level flight MRT 250K (Max.)
- Idle RPM descent ≈250 KOAS
- 1/2 lateral control 60°-60° rolls @ 250 KOAS, PLF
- Full lateral control 60°-60° rolls @ 250 KOAS, PLF
- Full lateral control 360° rolls, @ 250 KOAS, PLF

2nd Flight: Max. Altitude 30,000 ft.
Max. Speed 400 KOAS or .85 MN

*Perform the following maneuvers at 20,000, 25,000, and 30,000 ft.:

- Level flight MRT (no airspeed limit)
- Idle RPM descent ≈ 250 KOAS
- 1/2 lateral control 60°-60° rolls @ V_{max} MRT
- Full lateral control 60°-60° rolls @ V_{max} MRT
- Full lateral control 360° rolls @ V_{max} MRT

*Do not operate speed brakes above 20,000 ft.

Perform the following maneuver at 10,000 and 15,000 ft.:

- Full lateral control 60°-60° rolls @ MRT, 400 KOAS max.

3rd and Subsequent Flights

Flight Envelope: Sea level to 30,000 ft.

Airspeed: Up to 400 KOAS or 0.85 MN, whichever is less

Flight Maneuvers: At pilot's discretion

Flight Data

- Takeoffs and Landings:

  Record data continuously during 1st two minutes of takeoff and climb and continuously during the two minutes prior to touchdown (Flights 1 and 2 only).

- Flight: Record a 15 sec. data burst once every 10 min. (all flights)

- Maneuver: Record data continuously during maneuver.

Maneuvers for Pilot Comments

NOTE: Pilot to perform these at his discretion. Recorders not on. Pilot to comment after landing.

- Apply small lateral inputs, note response.

- Make comparison of "8000 psi feel" with "3000 psi feel".

- Turn aileron power "off" and fly manually. Compare with 3000 psi "feel".

- The pilot is encouraged to perform any additional maneuvers that would provide worthwhile data.

Post-Flight Checks

- Remove case drain filter bowl (8000 psi system). Take bowl, filter, and fluid to lab for patch test. (1st three flights and after final flight)

- Take fluid sample for contamination check (1st three flights and after final flight). Take sample within one hour after flight.

APPENDIX B

NADC CONFERENCE

A briefing conference covering the LHS and AFCAS development programs was held in June 1976 at the Naval Air Development Center, Warminster, Pennsylvania. The objective was to present the results, status, and planning of advanced concepts being pursued by NADC, References 1 through 12, and promote an exchange of views on high pressure hydraulics with prime contractors and major component suppliers. The three day meeting was attended by approximately 80 industry and government personnel.

Several presentations were given, and handout summaries were distributed. Subjects discussed and the presentor ( ) are listed below:

- Technology status of the AFCAS development program (NAVAIRSYSCOM)
- Backup flight controls for increased aircraft survivability (Honeywell, Inc.)
- Low cost, building block, control-by-wire actuators (Rockwell International)
- Electromechanical actuators for primary flight controls (McDonnell Douglas Electronics Co.)
- Laboratory demonstration of AFCAS hardware (Rockwell International)
- Technology status of the LHS development program (NAVAIRDEVCEN)
- Application study of the LHS concept to the F-14 airplane (Grumman Aerospace Corp.)
- 8000 psi component Test Results (Rockwell International)
- 8000 psi pump development (Abex Corporation)
- Pressure intensifier development (Sundstrand)
- High Pressure Effort (Sperry-Vickers)
- Gun fire tests on tubing containing 8000 psi pressure (NAVAIRDEVCEN)

- Pressure impulse and vibration testing of tubing, fittings, and hoses at 8000 psi (NAVAIRDEVCEN)

- Laboratory demonstration of 8000 psi components (Rockwell International)

- LHS advanced development program plan (NAVAIRDEVCEN)

The LHS advanced development phase will involve the design, fabrication, and qualification of components for a prototype 8000 psi hydraulic system. The system will then be evaluated in a simulator (iron bird), installed in a test bed aircraft, and flight tested. Successful completion of this program will substantiate the LHS concept, and provide information necessary to progress toward fleet use of the concept in the 1980's.